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STATE OF TECHNOLOGY REVIEW
SOIL VAPOR EXTRACTION SYSTEMS

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16. ABSTRACT

Soil vapor extraction is a cost-effective technique for the removal of volatile organic chemicals (VOCs) from contaminated soils. Among the advantages of the soil air extraction processes are that they create a minimal disturbance of the contaminated soil, they can be constructed from standard equipment, there is demonstrated experience with soil vapor extraction at pilot- and field-scale, they can be used to treat large volumes of soil than can be practically excavated, and there is a potential for product recovery. The experience with existing extraction systems has been reviewed and information about each system is briefly summarized.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementation, and management of research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Based on the current state of the technology of soil vapor extraction system, a number of conclusions can be made. Soil vapor extraction can be effectively used for removing a wide range of volatile chemicals over a wide range of conditions. The design and operation of these systems is flexible enough to allow for rapid change in operation thus, optimizing the removal of chemicals. While a number of variables intuitively effect the rates of chemical extraction, no extensive study to correlate variables to extraction rates has been identified.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

Soil vapor extraction is a cost-effective technique for the removal of volatile organic chemicals (VOCs) from contaminated soils. Among the advantages of the soil air extraction processes are that they create~~s~~ a minimal disturbance of the contaminated soil, they can be constructed from standard equipment, there is demonstrated experience with soil vapor extraction at pilot- and field-scale, they can be used to treat larger volumes of soil than can be practically excavated, and there is a potential for product recovery.

Unfortunately, there are few guidelines for the optimal design, installation, and operation of soil vapor extraction systems. A large number of pilot- and full-scale soil vapor extraction systems have been constructed and studied under a wide range of conditions. The major objectives of this report are to critically review available documents that describe current practices and to summarize this information as concisely as possible. A brief description of a typical vapor extraction system is presented. The experience with existing extraction systems has been reviewed, and information about each system is briefly summarized.

A soil vapor extraction system involves extraction of air containing volatile chemicals from unsaturated soil. Fresh air is injected or flows into the subsurface at locations around a spill site, and the vapor-laden air is withdrawn under vacuum from recovery or extraction wells. A typical soil vapor extraction system consists of: (1) one or more extraction wells, (2) one or more air inlet or injection wells (optional), (3) piping or air headers, (4) vacuum pumps or air blowers, (5) flow meters and controllers, (6) vacuum gauges, (7) sampling ports, (8) air/water separator (optional), (9) vapor treatment (optional), and (10) a cap (optional).

Based on the current state of the technology of soil vapor extraction systems, a number of conclusions can be made. Soil vapor extraction can be effectively used for removing a wide range of volatile chemicals over a wide range of conditions. The design and operation of these systems is flexible enough to allow for rapid changes in operation, thus, optimizing the removal of chemicals. Intermittent blower operation is probably more efficient in terms of removing the most chemical with the least energy, especially in systems where chemical transport is limited by diffusion through air or water. Air injection and capping a site have the advantage of controlling air movement, but injection systems need to be carefully designed. Incremental installation of wells, while probably more expensive, allows for a greater degree of freedom in design. While a number of variables intuitively affect the rate of chemical extraction, no extensive study to correlate variables to extraction rates has been identified.

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SECTION 1

INTRODUCTION

Soil may become contaminated with volatile organic chemicals such as industrial solvents and gasoline components in a number of ways. The sources of contamination at or near the earth's surface include intentional disposal, leaking underground storage tanks, and accidental spills. Contamination of groundwater from these sources can continue even after discharge has stopped because the unsaturated zone above a groundwater aquifer can retain a portion or all of the contaminant discharge. As rain infiltrates, chemicals elute from the contaminated soil and migrate towards groundwater.

Alternatives for decontaminating unsaturated soil include excavation with on-site or off-site treatment or disposal, biological degradation, and soil washing. Soil vapor extraction is also an accepted, cost-effective technique for the removal of volatile organic chemicals (VOCs) from contaminated soils (Bennedsen, 1987; Malot and Wood, 1985; Payne *et al*., 1986). Among the advantages of the soil air extraction process are that it creates a minimal disturbance of the contaminated soil, it can be constructed from standard equipment, there is demonstrated experience with the process at pilot- and field-scale, it can be used to treat larger volumes of soil than are practical for excavation, and there is a potential for product recovery. With vapor extraction, it is possible to clean up spills before the chemicals reach the groundwater table. Soil vapor extraction technology is often used in conjunction with other clean up technologies to provide complete restoration of contaminated sites (Malot and Wood, 1985; Oster and Wenck, 1988; CH_2M-Hill, 1987).

Unfortunately, there are few guidelines for the optimal design, installation, and operation of soil vapor extraction systems (Bennedsen, 1987). Theoretically-based design equations which define the limits of this technology are especially lacking. Because of this, the design of these systems is mostly empirical. Alternative designs can only be compared by the actual construction, operation, and monitoring of each design.

A large number of pilot- and full-scale soil vapor extraction systems have been constructed and studied under a wide range of conditions. The information gathered from this experience can be used to deduce the effectiveness of this technology. One of the major objectives of this report is to critically review available documents that describe current practices and to summarize this information as concisely as possible. A brief description of a typical vapor extraction system is presented. The experience with existing extraction systems has been reviewed, and information about each system is briefly summarized in a standard form. The information is further summarized in several tables, which form the basis for a discussion of the design, installation, and operation of these systems. Because soil vapor extraction is a relatively new soil remediation technology, this document will evolve as more information becomes available.

SECTION 2

PROCESS DESCRIPTION

A soil vapor extraction, forced air venting, or in-situ air stripping system, such as the one shown conceptually in Figure 1, revolves around the extraction of air containing volatile chemicals from unsaturated soil. Fresh air is injected or flows into the subsurface at locations around a spill site, and the vapor-laden air is withdrawn under vacuum from recovery or extraction wells.

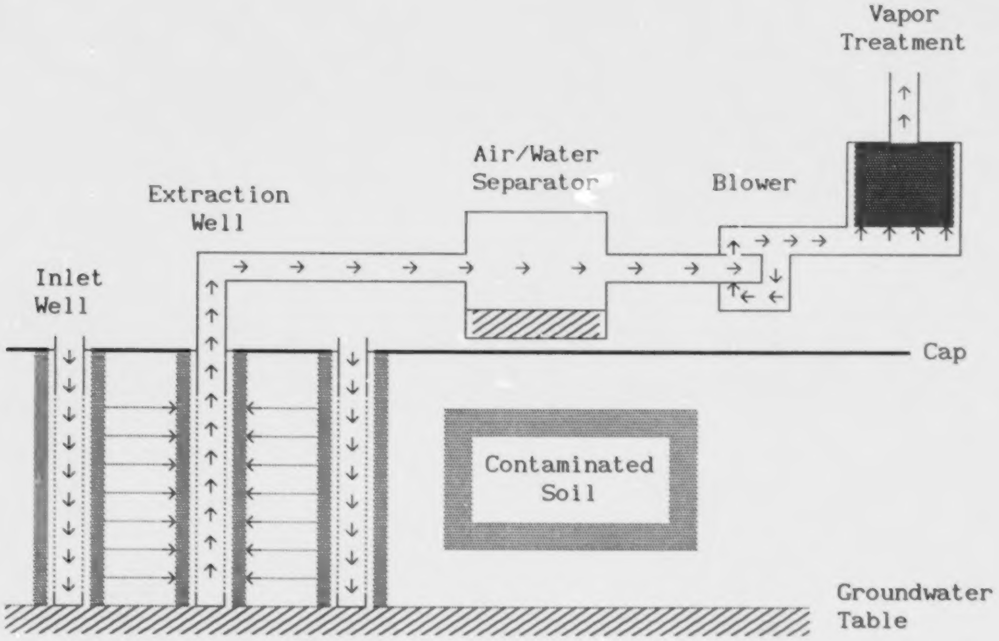

Vapor
Treatment
Air/Water
Separator
Blower
Extraction
Well
Inlet
Well
Cap
Contaminated
Soil
Groundwater
Table

Figure 1. Soil Vapor Extraction System

SYSTEM COMPONENTS

A typical soil vapor extraction system such as the one shown in Figure 1 consists of: (1) one or more extraction wells, (2) one or more air inlet or injection wells (optional), (3) piping or air headers, (4) vacuum pumps or air blowers, (5) flow meters and controllers, (6) vacuum gauges, (7) sampling ports, (8) air/water separator (optional), (9) vapor treatment (optional), and (10) a cap (optional). Extraction wells are typically designed to fully penetrate the unsaturated zone to the capillary fringe. If the groundwater is at a shallow depth or if the contamination is confined to near-surface soils, then the extraction wells may be placed horizontally. Extraction wells usually consist of slotted, plastic pipe placed in permeable packing. The surface of the augured column for vertical wells or the trench for horizontal wells is usually grouted to prevent the direct inflow of air from the surface along the well casing or through the trench.

It may be desirable to also install air inlet or injection wells to control air flow through zones of maximum contamination. They are constructed similarly to the extraction wells. Inlet wells or vents are passive and allow air to be drawn into the ground at specific locations. Injection wells force air into the ground and can be used in closed-loop systems (Payne *et al.*, 1986). The function of inlet and injection wells is to enhance air movement in strategic locations and promote horizontal air flow to the extraction wells.

Piping material connecting the wells to headers is usually plastic. The headers are connected to the blowers or pumps and may be plastic or steel. Pipes and headers may be buried or wrapped with heat tape and insulated in northern climates to prevent freezing of condensate.

The pumps or blowers reduce gas pressure in the extraction wells and induce air flow to the wells. The pressure from the outlet side of the pumps or blowers can be used to push the exit gas through a treatment system and back into the ground if injection wells are used.

Gas flow meters are installed to measure the volume of extracted air. Ball or butterfly valves are used to adjust flow from or into individual wells. Pressure losses in the overall system are measured with vacuum gauges. Sampling ports may be installed in the system at each well head, at the blower, and after vapor treatment. In addition, vapor and pressure monitoring probes may be placed to measure soil vapor concentrations and the radius of influence of the vacuum in the extraction wells.

To protect the blowers or pumps and to increase the efficiency of vapor treatment systems, an air/water separator may need to be installed. The condensate may then have to be treated as a hazardous waste depending on the types and concentrations of contaminants. The need for a separator may be eliminated by covering the treatment area with an impermeable cap or by designing the extraction wells to separate water from air within the well packing. An impermeable cap serves to cover the treatment site to minimize infiltration and controls the horizontal movement of inlet air.

Vapor treatment may not be required if the emission rates of chemicals are low or if they are easily degraded in the atmosphere. Typical treatment systems include liquid/vapor condensation, incineration, catalytic conversion, or granular activated carbon adsorption.

SYSTEM OPERATION

During operation, the blower is turned on, and the air flows come to equilibrium. The flows that are finally established are a function of the equipment, the flow control devices, the geometry of well layout, the site characteristics, and the air-permeability of the soil. Exhaust air is sampled on a routine basis and used along with flow measurements to determine the rate of VOC extraction. Typically, the rate of chemical extraction is high at first and subsequently decreases because the rate becomes limited by diffusion of VOC out of immobile air and water zones. In those cases where extraction is diffusion-limited, the blower can be turned on and off to conserve energy. At the end of operation, the final distribution of VOCs in the soil can be measured to ensure decontamination of the site.

SYSTEM VARIABLES

A number of variables characterize the successful design and operation of a vapor extraction system. They may be classified as site conditions, soil properties, chemical characteristics, control variables, and response variables (Anastos *et al*., 1985; Enviresponse, 1987). Table 1 lists specific variables that belong to these groups.

Most site conditions can not be changed. The extent to which VOCs are dispersed in the soil, vertically and horizontally, is an important consideration in deciding if vapor extraction is preferable to other methods. Soil excavation and treatment is probably more cost effective when only a few hundred cubic yards of near-surface soils are contaminated (Bennedsen, 1987). If the spill has penetrated more than 20 or 30 feet or has spread through an area over several hundred square feet at a particular depth or if the spill volume is in excess of 500 cubic yards, then excavation costs begin to exceed those associated with a vapor extraction system (CH_2M-Hill, 1985; Payne *et al*., 1986). The depth to groundwater is also important. Where groundwater is at depths of more than 40 feet and the contamination extends to the groundwater, use of soil vapor extraction systems may be one of the few ways to remove VOCs from the soil (Malot and Wood, 1985). Groundwater depth in some cases may be lowered to increase the volume of the unsaturated zone. The water infiltration rate can be controlled by placing an impermeable cap over the site. Heterogeneities influence air movement as well as the location of chemical, and the presence of heterogeneities make it more difficult to position extraction and inlet wells. There generally will be significant differences in the air conductivity of the various strata of a stratified soil. A horizontally- stratified soil may be favorable for vapor extraction because the relatively impervious strata will limit the rate of vertical inflow from the ground surface and will tend to extend the influence of the applied vacuum horizontally from the point of extraction. The specific location of the contaminant on a property and the type and extent of development in the vicinity of the contamination, may favor the installation

TABLE 1. SOIL VAPOR EXTRACTION SYSTEM VARIABLES

Site Conditions
Distribution of VOCs
Depth to groundwater
Infiltration rate
Location of Heterogeneities
Temperature
Atmospheric pressure

Soil Properties
Permeability (air and water)
Porosity
Organic carbon content
Soil structure
Soil moisture characteristics
Particle size distribution

Chemical Properties
Henry's constant
Solubility
Adsorption equilibrium
Diffusivity (air and water)
Density
Viscosity

Control Variables
Air withdrawal rate
Well configuration
Extraction well spacing
Vent well spacing
Ground surface covering
Pumping duration
Inlet air VOC concentration and moisture content

Response Variables
Pressure gradients
Final distribution of VOCs
Final moisture content
Extracted air concentration
Extracted air moisture
Extracted air temperature
Power usage

of a soil vapor extraction system. For example, if the contamination extends across property lines, beneath a building or beneath an extensive utility trench network, vapor extraction should be considered. Temperature affects the performance of soil vapor extraction system primarily because of its influence on chemical properties such as Henry's constant, solubility, and sorption capacity. In most cases, extraction systems are operated at ambient temperatures. Atmospheric pressure fluctuations can affect air movement and depth of the groundwater table (Weeks, 1979).

The soil characteristics at a particular site will have a significant effect on the applicability of vapor extraction systems. Air conductivity controls the rate at which air can be drawn from soil by the applied vacuum. Grain size, moisture content, soil aggregation, and stratification probably are the most important properties (Bennedsen *et al.*, 1985; Hutzler *et al.*, 1988). The soil moisture content or degree of saturation is also important in that it is easier to draw air through drier soils. As the size of a soil aggregate increases, the time required for diffusion of the chemical out of the immobile regions also increases. However, even clayey or silty soils may be effectively ventilated by the usual levels of vacuum developed in a soil vapor extraction system (Camp, Dresser, and McKee, 1987; Terra Vac, 1986b). The success of the soil vapor extraction in these soils may depend on the presence of more conductive strata, as would be expected in alluvial settings, or on relatively low moisture contents in the finer-grained soils.

In conjunction with site conditions and soil properties, chemical properties will dictate whether a soil vapor extraction system is feasible. A vapor-phase vacuum extraction system is most effective at removing compounds that exhibit significant volatility at the ambient temperatures in soil. Low molecular weight, volatile compounds are favored, and vapor extraction is likely to be most effective at new sites where the more volatile compounds are still present. It has been suggested that compounds exhibiting vapor pressures over 0.5 mm of mercury can most likely be extracted with soil air (Bennedsen *et al*., 1985). When expressed in terms of the air-water partitioning coefficient, compounds which have values of dimensionless Henry's Law constants greater than 0.01 are more likely to be removed in vapor extraction systems. Examples of compounds which have been effectively removed by vapor extraction include trichloroethene, trichloroethane, tetrachloroethene, and most gasoline constituents. Compounds which are less applicable to removal include trichlorobenzene, acetone, and heavier petroleum fuels (Payne *et al*., 1986; Bennedsen *et al*., 1985; Texas Research Institute, 1980). Soluble compounds tend to travel farther in soils where the infiltration rate is high. The movement of chemicals with affinity for soil organic material or mineral adsorption sites will be retarded. In drier soils, chemical density and viscosity have the greatest impact on organic liquid movement, however, in most current systems, the contamination is old enough that no further movement of free product occurs.

Soil vapor extraction processes are flexible in that several variables can be adjusted during design or operation. These variables include the air withdrawal rate, the well spacing and configuration, the control of water infiltration by capping, and the pumping duration. Higher air flow rates tend to increase vapor removal because the zone of influence is increased and air is forced through more of the air-filled pores. More wells will allow better control of air flow but will also increase construction and operation costs. Intermittent operation of the blowers will allow time for chemicals to diffuse from immobile water and air and permit removal at higher concentrations.

Parameters responding to soil vapor extraction system performance include: air pressure gradients, VOC concentrations, moisture content, and power usage. The rate of vapor removal is expected to be primarily affected by the chemical's volatility, its sorptive capacity onto soil, the air flow rate, the distribution of air flow, the initial distribution of chemical, soil stratification or aggregation, and the soil moisture content.

SECTION 3

STATE OF THE TECHNOLOGY REVIEW

As a part of this investigation, information on 7 pilot-scale, and 10 field (full-scale) studies have been reviewed with respect to the design and operational variables listed in Table 1. These sites along with their location, the study type, the duration of study or date the study began, and the project status are listed in Table 2. This list is by no means complete. A number of other full-scale soil vapor extraction systems have since been identified. Full reports were either not available or the available reports had not been reviewed at the time of this report.

While this technology has been referred to by several names, including "subsurface venting", "vacuum extraction", "*in situ* soil air stripping", and "soil venting", the term "soil vapor extraction" seems to be most descriptive and is used in this report. Soil vapor extraction technology seems rather simple in concept, but its application appears to be relatively recent as indicated by the dates of the available reports. There is a wide variety of system designs and operating conditions.

From Table 2, it can be seen that soil vapor extraction systems have been installed at locations across the United States and have been observed over periods ranging from several weeks to several years. Projects ranging in status from being complete to being in the preliminary design stage have been identified. Some of the studies were too short to fully assess the effectiveness of this technology. Brief descriptions of each study were compiled in a standard format document of two to six pages (Table 3) to systematically catalog the information contained in the various reports.

The information on the site data sheets is further summarized in a number of tables to make it easier to compare specific design and operational variables. This leads to a more detailed discussion of the design, installation, and operation of soil vapor extraction systems.

SOIL VAPOR EXTRACTION SYSTEM DESIGN

Tables 4, 5, and 6 summarize the design and operation of the major components of the pilot- and field-scale systems reviewed for this report. These include extraction well design and placement, piping and blower systems and the miscellaneous components discussed previously.

TABLE 2. LIST OF TYPICAL PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS.

SITE	LOCATION	STUDY TYPE	DATE OR DURATION	STATUS	REFERENCES	NAME USED FOR SYSTEM
FUEL MARKETING TERMINAL	Granger Indiana	pilot	12 days 10 days 15 days	completed	Crow et al., 1987 Amer Petr Inst, 1985	Subsurface Venting
VALLEY MANUFACTURING	Groveland Massachusetts	pilot	Jan-Apr 88	data being compiled	Enviresponse, 1987	Vacuum Extraction
INDUSTRIAL TANK FARM	San Juan Puerto Rico	pilot/ field	30 months	completed?	Malot & Wood, 1985 Malot, 1985	Vacuum Extraction
TIME OIL COMPANY	Tacoma Washington	pilot/ field	11 days (Aug 1985)	pilot completed	Woodward-Clyde, 1985	Soil Gas Vapor Extraction
SOLVENTS STORAGE TANK	Cupertino California	pilot/ field	several months	completed?	Bennedsen, 1987	Soil Gas Vapor Extraction
TCAAP PILOT 1	New Brighton Minnesota	pilot	67 days	completed	Anastos et al., 1985	In-situ Venting
TCAAP PILOT 2	"	pilot	78 days	completed	Anastos et al., 1985	"
TCAAP SITE D	"	field	Feb 1986	ongoing	Wenck, 1985 Oster & Wenck, 1988	"
TCAAP SITE G	"	field	Feb 1986	ongoing	Wenck, 1985 Oster & Wenck, 1988	"
GAS STATION	unknown	field	?	completed?	Malot & Wood, 1985	Vacuum Extraction
UNION 76 GAS STATION	Bellview Florida	field	7 months	ongoing	Camp, Dresser, & McKee, 1987, 1988	Vacuum Extraction
SOUTH PACIFIC RAILROAD	Benson Arizona	field	7 months	completed	Johnson, 1988 Johnson & Sterrett, 1988	In-situ Soil Air Stripping
CUSTOM PRODUCTS	Stevensville Michigan	field	Dec 1988 >280 days	completed?	Payne et al., 1986 Payne & Lisiecki, 1988	Forced Air Circulation
ELECTRONIC MANUFACTURING	Santa Clara Valley, CA	field	3 yrs	completed?	Bennedsen, 1985	Vapor Extraction
PAINT STORAGE	Dayton Ohio	field	since July 1987	ongoing	Payne & Lisiecki, 1988	Enhanced Volatilization
THOMAS SOLVENT COMPANY	Battle Creek Michigan	field	since Jan 1988	ongoing	CH_2M-Hill, 1987	Vacuum Extraction
HILL AFB VERTICAL VENTS	Hill AFB	field	Fall 1988	one-well vent test completed	Oak Ridge National Lab, 1988 Radian, Corp., 1987	Soil Venting
HILL AFB LATERAL SYSTEM	(3 parallel) (extraction) (systems)	"	"			"
HILL AFB SOIL PILE		"	"			"

TABLE 3. SITE DATA SHEET FORMAT

ASSESSMENT OF PILOT- OR FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Each site or project is identified by the name of the particular site or study.

Principal Investigator(s): In this section, full names of individuals performing the studies, along with their business addresses are given.

Investigative Report(s): Each report or paper pertaining to the particular site or project is listed.

Location of Work/Study: The general location of each site or project is given.

Nature of Contamination: Information on the source of contamination, the volume of the spill or contaminated soil, the type of contaminants, the levels of contamination, and the location is summarized as well as possible.

Soil/Site Conditions: Details on the type of soil strata at the site, the depth of the groundwater table, the porosity and permeability, the moisture content, and any obstructions present at the site are presented.

Experimental/System Design: The basic components of the particular soil vapor extraction system are listed. A detailed discussion of the specific system design follows, including system drawings, if available.

Status of Experimental/Site Clean-up: This section details the final or current clean-up levels at the site.

Well Design and Placement

Table 4 summarizes information on the design and placement of extraction and injection wells at the sites listed in Table 2.

Extraction Wells --

Typically, extraction wells are designed to fully penetrate the unsaturated soil zone or the geologic stratum to be cleaned. An extraction well usually is constructed of slotted plastic pipe. The well screen is placed in a permeable packing as shown in Figure 2. Wells may be aligned vertically or horizontally. Vertical alignment is typical for deeper contamination zones and results in radial flow patterns. If the depth of the contaminated soil or the depth to the groundwater table is less than 10 to 15 feet, it may be more practical to dig a trench across the area of contamination and install perforated piping in the trench bottom versus

TABLE 4. PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS -- WELL DESIGN AND PLACEMENT

SITE	EXTRACTION WELLS				AIR INPUT		
	NUMBER AND TYPE	WELL MATERIAL	WELL CONSTRUCTION	WELL SPACING	NUMBER AND TYPE	WELL MATERIAL	WELL CONSTRUCTION
FUEL MARKETING TERMINAL	2 wells	2" PVC	screened 14 to 20 ft BLS	20, 40, & 100 ft	4 air inlet wells	2" PVC	screened 14 - 20 ft BLS
VALLEY MANUFACTURING	8 wells 4 sh, 4 deep	4" PVC	up to 30 ft deep	20 ft	surface	na	na
INDUSTRIAL TANK FARM	3 wells	?	25 to 75 ft BLS & at 300 ft BLS	?	surface	na	na
TIME OIL COMPANY	7 wells	2" PVC	screened 6 to 25 ft BLS	40-90 ft	surface	na	na
SOLVENTS STORAGE TANK	1 well	?	?	na	1 air inlet well	?	?
TCAAP PILOT 1	9 well grid	3" PVC	grav. pack, slotted 5 to 20 ft BLS	20 ft	4 wells	3" PVC	slotted 15 - 20 ft BLS
TCAAP PILOT 2	9 well grid	3" PVC	grav. pack, slotted 5 to 20 ft BLS	50 ft	4 wells	3" PVC	slotted 15 - 20 ft BLS
TCAAP SITE D	39 wells	3" PVC	grav. pack, slotted 5 to 25 - 35 ft BLS	25 ft	surface or air inlet	vents can be air inlets	same as extraction
TCAAP SITE G	89 wells	3" PVC	grav. pack, slotted 5 - 25 to 35 ft BLS	25 ft	surface or air inlet	vents can be air inlets	same as extraction
GAS STATION	vertical & horizontal	?	?	?	surface	na	na
UNION 76 GAS STATION	6 wells 3 sh, 3 deep	4" PVC	slotted 10 to 15 ft	14-50 ft	surface	na	na
SOUTH PACIFIC RAILROAD	79 wells	2" PVC	15 to 25 ft deep	variable	surface & injection	21 vents were used as AIW	same as extraction
CUSTOM PRODUCTS	1 well	2" galv. steel	gravel pack 8 to 25 ft BLS	50-70 ft	6 air inj. wells	1.25" PVC	gravel pack 15 to 25 ft BLS
ELECTRONIC MANUFACTURING	1 to 2 wells	2" diam.	?	?	1 to 2 air inlets	2" diam.	?
PAINT STORAGE	over 20 wells	galv. steel	?	?	large no. of wells	poly-ethylene	?
THOMAS SOLVENT COMPANY	14 wells	4" PVC	?	?	surface	na	na
HILL AFB VERTICAL VENTS	15 vertical vent wells	4" PVC	screened 10 to 30 ft BLS	20 and 40 ft	surface or air inlet	vents can be air inlets	same as extraction
HILL AFB LATERAL SYSTEM	6 laterals	4" poly-ethylene	20 ft BLS	15 ft	surface or air inlet	laterals can be inlets	same as extraction
HILL AFB SOIL PILE	8 laterals	4" poly-ethylene	5 ft above pile bottom	18 ft	surface	na	na

AIW -- air inlet well	GWT -- ground water table	? -- no information
BLS -- below land surface	na -- not applicable	sh -- shallow

installing vertical extraction wells (Oak Ridge National Lab, 1988; Connor, 1988). Usually several wells are installed at a site, especially if soil strata are highly variable in terms of permeability. In stratified systems, more than one well may be installed in the same location, each venting a given strata (Camp, Dresser, and McKee, 1987, 1988). Extraction wells can be installed incrementally starting with installation in the area of highest contamination (Payne and Lisiecki, 1988; Johnson and Sterrett, 1988). This allows the system to be brought on-line as soon as possible.

Well spacing is usually based on an estimate of the radius of influence of an individual extraction well (Malot and Wood, 1985; Wenck, 1985; Oak Ridge National Lab, 1988). In the studies reviewed, well spacing has ranged from 15 to 100 feet. Johnson and Sterrett (1988) suggest that well spacing should be decreased as soil bulk density increases or the porosity of the soil decreases.

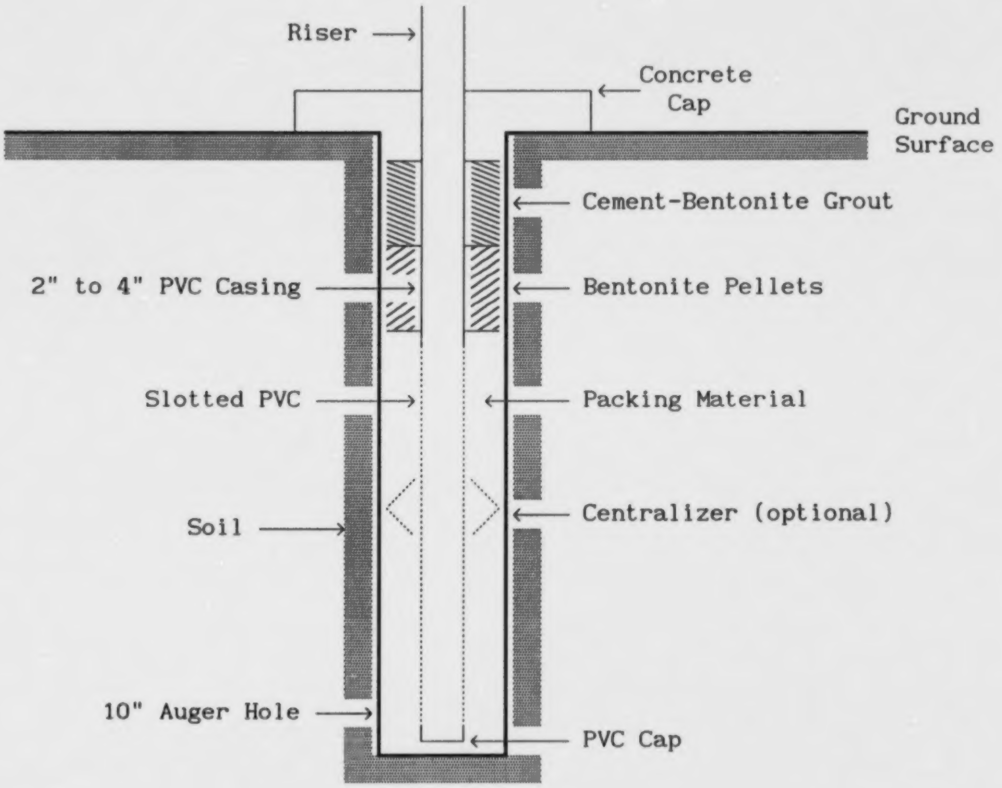

Riser
Concrete Cap
Ground Surface
Cement-Bentonite Grout
2" to 4" PVC Casing
Bentonite Pellets
Slotted PVC
Packing Material
Soil
Centralizer (optional)
10" Auger Hole
PVC Cap

Figure 2. Typical Extraction/Air Inlet Well Construction.

One of the major differences noted between systems was the soil boring diameter. Larger borings are preferred to provide air/water separation in the packing.

Air Input --

In the simplest soil vapor extraction systems, air flows to an extraction well from the ground surface as depicted in Figure 3. To enhance air flow through zones of maximum contamination, it may be desirable to include air inlet wells in the installation. Injection wells or air vents may be located at numerous places around the site. The function of inlet wells and caps is to control the flow of air into a contaminated zone. Air vents are passive; whereas, injection wells force air into the ground at the edge of a site, as depicted in Figure 4, so as not to force contamination away from the extraction wells. In addition, injection wells are often installed between adjacent extraction wells to ensure pressure gradients in the direction of the extraction wells (Payne *et al.*, 1986). Typically, injection wells and air vents are similar in construction to extraction wells. In some installations, extraction wells have been designed so they can be also be used as air inlets (Wenck, 1985; Oak Ridge National Lab, 1988).

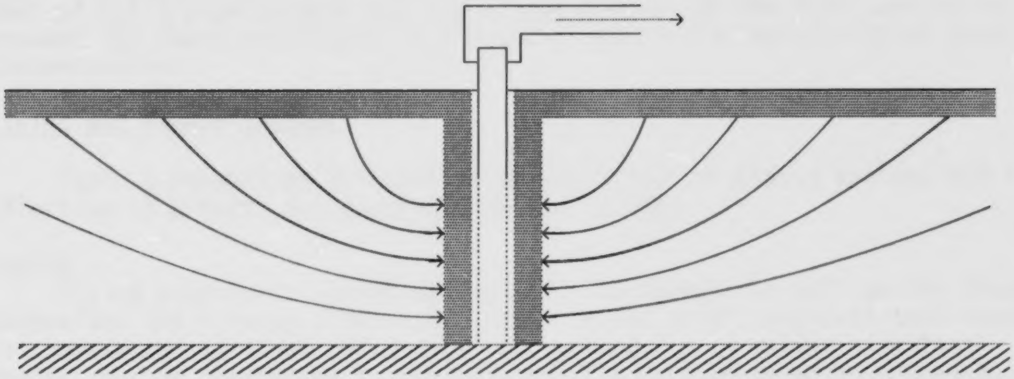


Figure 3. Air Flow Patterns in Vicinity of a Single Extraction Well -- No Cap.

Usually, only a fraction of extracted air comes from air inlets (American Petroleum Institute, 1985; Crow *et al.*, 1987; Ellgas and Marachi, 1988). This indicates that air drawn from the surface is the predominant source of clean air.

Thortan *et al.* (1984) investigated the effects of air flow rate, and the configuration of the inlet and extraction wells on gasoline recovery from an artificial aquifer. They determined that screening geometry only had an effect at the low air flow rates. At low flow rates, higher recovery rates resulted when the screen was placed near the water table versus being screened

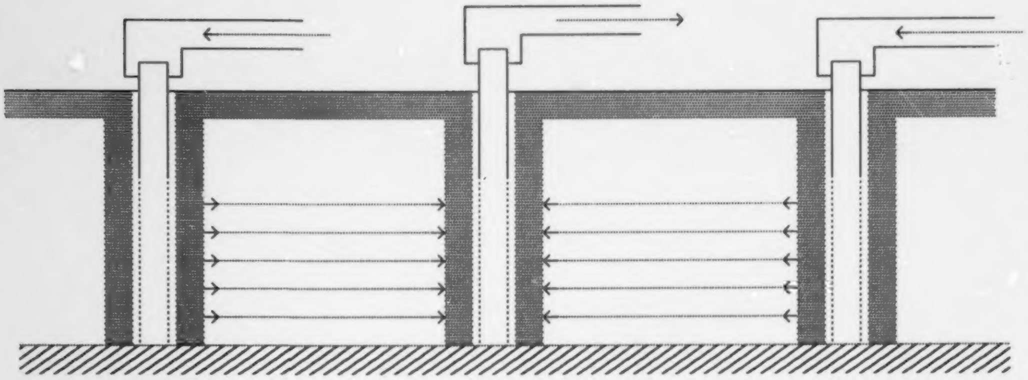


Figure 4. Air Flow from Injection Wells.

the full depth of the aquifer. A similar assessment was made by Woodward-Clyde Consultants (1985) at the Time Oil Company site. Woodward-Clyde engineers suggested that the wells should be constructed with approximately 20 feet of solid pipe between the top of the screen and the soil surface to prevent the short circuiting of air and to aid in the extraction of deep contamination.

Piping and Blower Systems

Table 5 summarizes information on the design of piping systems and the selection of blowers for vapor extraction systems.

Piping --

Piping materials connecting the wells to headers as well as the headers themselves are usually plastic or steel. Wenck (1985) suggests that headers be constructed of steel for durability, especially in colder climates. Headers may be configured as manifold or in a grid as shown in Figure 5, although, manifold construction appears to be the most common. Pipes and headers are usually buried or wrapped with heat tape and insulated in northern climates to prevent freezing of condensate (Wenck, 1985).

Valving --

A control/shut-off valve is usually installed at each wellhead and at other critical locations, such as lateral/header connections, to provide operational flexibility and optimize extraction rates. Typically, ball or butterfly valves are used because they provide better flow control.

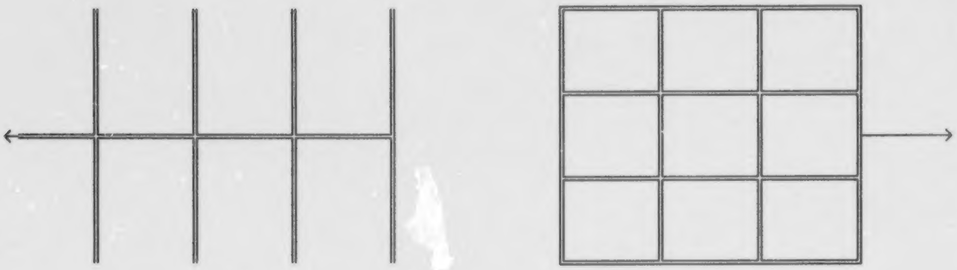
Vacuum Source --

The vacuum for extracting soil air is developed by an ordinary positive displacement industrial blower, a rotary blower, vacuum or aspirator pump, or a turbine. There are a large number of commercially available blower models. In the studies reported herein, the blowers have had ratings ranging from 100 to 6,000 cubic feet per minute at vacuums up to about 30 inches Hg gauge as

TABLE 5. PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS -- PIPING AND BLOWER SYSTEMS

SITE	PIPING	VACUUM SOURCE	AIR FLOW	VACUUM	GAS FLOW METER
FUEL MARKETING TERMINAL	1 & 2" PVC	2 liquid ring vacuum pumps	23 cfm 18 cfm 40 cfm	0.4" Hg 0.3" Hg 0.9" Hg	pitot tube w/ diff. press. meas
VALLEY MANUFACTURING	PVC manifold heated	blower	3 to 800 cfm?	0-29" Hg	X
INDUSTRIAL TANK FARM	?	vacuum pump	18 cfm 150 cfm	25-30" Hg	?
TIME OIL COMPANY	2" PVC manifold	blower	210 cfm 30 cfm/well	?	pitot tube w/ diff. press. meas
SOLVENTS STORAGE TANK	?	blowers	10 cfm 100 cfm	0.24" Hg 6" Hg	?
TCAAP PILOT 1	3" PVC grid insulated	2 blowers 1 extr., 1 inj.	40 - 55 cfm	?	X
TCAAP PILOT 2	3" PVC grid insulated	2 blowers 1 extr., 1 inj.	200-220 to 100 to 50 cfm	?	X
TCAAP SITE D	8 to 18" steel insul. manifold heated	up to 4 blowers variable speed	2200 cfm per blower	1.8" Hg	totalizing flow meter
TCAAP SITE G	12 to 24" steel insul. manifold heated	up to 4 blowers variable speed	5700 cfm per blower	1.8" Hg	totalizing flow meter
GAS STATION	?	vacuum pump	?	?	?
UNION 76 GAS STATION	manifold	vacuum pump	?	?	?
SOUTH PACIFIC RAILROAD	4" PVC manifold	3 blowers separate systems	86 - 250 cfm	0.7-0.6" Hg	none
CUSTOM PRODUCTS	2" galv. steel	rotary vane vac. pump	10.2 cfm	4.5" Hg	X
ELECTRONIC MANUFACTURING	duct	2 blowers	10 cfm to 100 cfm	0.2 to 3" Hg	?
PAINT STORAGE	galv. st., heat manifolds	8 blowers	?	?	?
THOMAS SOLVENT COMPANY	?	blower	?	?	?
HILL AFB VERTICAL VENTS	10-16" metal manifold	common source 3 rotary lobe blowers 1000 cfm each	up to 3000 cfm	9" Hg	orifices with Magnehelic differential pressure gauges or U-tube manometers
HILL AFB LATERAL SYSTEM	same				
HILL AFB SOIL PILE	same	250 cfm aux. blower			

X -- listed component present, no detailed information
? -- no information



a) Manifold b) Grid

Figure 5. Piping Structures

shown in Table 5. Ratings of the electric drive motors are usually 10 horsepower or less. The pressure from the outlet side of the pumps or blowers is usually used to push the exit gas through a treatment system and can be used to force air back into the ground if injection wells are used (Payne *et al.*, 1986), although, it is more common to use a separate blower for injection (Anastos *et al.*, 1985). Vapor treatment efficiency can be improved by installing the blower between the moisture separator and the vapor treatment system to take advantage of the heat generated by the blower. The blower or blowers are usually housed in a temporary building on-site.

Gas Flow Meter --

A flow meter should be installed to monitor the volume of extracted air. This measurement is used in conjunction with gas analysis to determine the total mass of vapor extracted from the soil. Flow measurements from individual wells are useful for optimizing extraction system operation. A flowmeter consisting of an orifice plate and manometer, together with the appropriate rating curve, will yield the system discharge air flow rate.

Miscellaneous Components

In addition to the basic well, piping, and blower components, a soil vapor extraction system may require a cover, air/water separator, and vapor treatment. Table 6 summarizes the range of design of miscellaneous components at the various pilot- and field systems.

Impermeable Cap --

The surface of the entire site may be sealed with plastic sheeting, clay, concrete, or asphalt as indicated in Table 6. If movement of the air toward the extraction well is desired to be more radial than vertical, then an impermeable cap should be added. The cap controls the air flow pathway so that make-up or clean air is more likely to come from air vents or injection

TABLE 6. PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS -- MISCELLANEOUS COMPONENTS

SITE	IMPERMEABLE CAP	AIR/WATER SEPARATOR	VAPOR TREATMENT	GAUGES	SAMPLING PORTS	TYPES OF MONITORING
FUEL MARKETING TERMINAL	plastic membrane	none	none	vacuum temperature	well heads exhaust port	monitoring well vapor probes
VALLEY MANUFACTURING	none	500 gallon	GAC	vacuum	well head system lines	exhaust gas monitoring wells
INDUSTRIAL TANK FARM	none	condenser	recovery tank	?	?	exhaust gas monitoring wells
TIME OIL COMPANY	none	55 gallon tank	none	vacuum temperature	well heads exhaust port	soil borings exhaust gas
SOLVENTS STORAGE TANK	none	55 gallon tank	none	?	?	exhaust gas
TCAAP PILOT 1	?	none	GAC	vacuum temperature	inlet ports exhaust port	soil borings air monitoring
TCAAP PILOT 2	?	none	GAC	vacuum temperature	inlet ports exhaust port	soil borings air monitoring
TCAAP SITE D	18" clay	none	none	vacuum	well heads central header	soil vapor air monitoring exhaust gas
TCAAP SITE G	18" clay	none	none/GAC	vacuum	well heads central header	soil vapor air monitoring exhaust gas
GAS STATION	concrete pavement	condenser?	none	?	?	monitoring wells
UNION 76 GAS STATION	existing pavement	gas/water separator	none	?	?	monitoring wells soil borings vapor probes
SOUTH PACIFIC RAILROAD	none	none	none	?	?	monitoring wells soil borings
CUSTOM PRODUCTS	6 mil-polyethylene	liquid trap	GAC	vacuum	before and after GAC	exhaust gas soil samples
ELECTRONIC MANUFACTURING	none	none	none	vacuum	exhaust	exhaust gas
PAINT STORAGE	clay cover & concrete	trap w/pump to tank	combustion	vacuum temperature	well heads vapor, water	monitoring wells soil borings
THOMAS SOLVENT COMPANY	none	none	GAC	vacuum temperature	exhaust GAC outlets	monitoring wells soil borings air monitoring
HILL AFB VERTICAL VENTS	80'x 140' plastic	50 gallon knock-out drum	catalytic incinerator	vacuum temperature humidity	well heads exhaust	pressure monitoring wells
HILL AFB LATERAL SYSTEM	concrete tank pad	"	GAC?	"	"	soil borings
HILL AFB SOIL PILE	none	"	"	"	"	

GAC -- granular activated carbon
? -- no information

wells. This is depicted in Figures 3 and 6. Without the cap (Figure 3), a more vertical movement of air from the soil surface takes place. But when an impermeable cap is in place, the radius of influence around the extraction well is extended (Figure 6). Thus, more of the contaminated soil may be cleansed by the air flow. If direct flow of air from the ground surface to the extraction well limits the effectiveness of the extraction system, it may be necessary to cap or cover the surface. The use of a polyethylene cover will also prevent or minimize infiltration, which, in turn, reduces the moisture content and further chemical migration. With little or no infiltration, water is less likely to be extracted from the system, thus reducing the need for an air/water separator. In very dry climates, a reduction of moisture content below which partial drying of the soil occurs, extraction system efficiency may be reduced due to increased adsorption capacity of the dry soil (Johnson and Sterrett, 1988).

Air/Water Separator --

If water is pulled from the extraction wells, an air/water separator is required to protect the blowers or pumps and to increase the efficiency of vapor treatment systems. The condensate may then have to be treated as a hazardous waste depending on the types and concentrations of contaminants. The need for a separator may be eliminated by covering the treatment area with an impermeable cap. In some cases, a gasoline/water separator may be used in conjunction with a combination vapor extraction/pumping system for gasoline product recovery (Malot and Wood, 1985; Thornton *et al*., 1984).

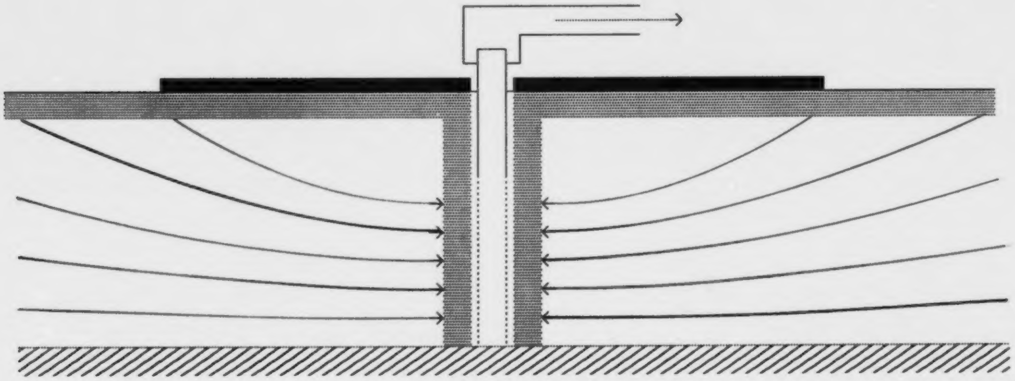


Figure 6. Air Flow Patterns With Impermeable Cap in Place.

Vapor Treatment --

Air emission problems should not be created solving a soil contamination problem. Vapor treatment may not be required for systems that produce a very low emission rate of easily degradable chemicals. The decision to treat vapor must be made in conjunction with air quality regulators. There are several treatment systems available that limit or control air emissions. These include liquid/vapor condensers, incinerators, catalytic converters, and gas-phase granular activated carbon (GAC). If air emissions control or vapor treatment is required for an installation, a vapor phase activated carbon adsorber system probably will be the most practical system depending on chemical emission rates and VOC levels, although catalytic oxidation units have produced favorable results (Bennedsen, 1985). Gas-phase GAC may require heating of the extracted air to control the relative humidity in order to optimize the carbon usage rate. As the fraction of water increases, the capacity for the target chemical decreases and the carbon replacement rate increases. The spent carbon may be considered as a hazardous waste depending on the contaminants (Enviresponse, 1987). On one project, where the initial extraction rate of volatiles was over 200 pounds per day, the extracted gas was able to be piped to the combustion air intake zone of a nearby industrial boiler that was in continuous operation (Bennedsen, 1985). Laboratory analyses did not detect unwanted volatiles in the boiler emissions. Incineration can be self-sustained combustion if the vapor contains high concentrations of hydrocarbons or combustible volatile chemicals. Usually there is a lag time to achieve a high concentration of combustibles. Concentration of volatiles in the air stream might be increased by intermittent blower operation or by intermittently operating different extraction wells. Some systems have auxiliary fuels to maintain a desired exhaust temperature.

Pitot Tubes and Pressure Gauges --
Various monitoring devices such as sampling ports, vacuum gauges, and pitot tubes for estimating vapor discharges are required. Pressure gauges are required to monitor the pressure losses in the overall system to optimize air flows.

Sampling Ports --
Sampling ports are usually installed at each well head, at the blower, and after gas treatment. The basic measurements required to assess soil vapor extraction system performance are the system air flow rate and the concentration of volatile organic chemicals in the extracted flow. A gas chromatograph equipped with an appropriate detector for the compounds expected to be present in the exhaust gas is typically used to provide VOC concentration data.

Monitoring Systems --
Vapor and pressure monitoring probes may be placed in the soil surrounding the extraction system to measure vapor concentrations and the radius of influence of the extraction wells. The monitoring wells are usually required to assess the final clean-up of a particular site.

SITE CONDITIONS

Soil and Geological Conditions

Table 7 briefly summarizes the geologic conditions at the various pilot and field sites. Although, it has been suggested that soil vapor extraction systems should be used primarily in highly permeable soils, they have been

TABLE 7. PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS -- SOIL AND GEOLOGICAL CONDITIONS

SITE	SOIL/ GEOLOGY	GWT DEPTH	SOIL POROSITY	HYDRAULIC CONDUCTIVITY	MOISTURE CONTENT	AREA AFFECTED
FUEL MARKETING TERMINAL	sand and fine sand layers w/ traces of clay and silt	25 ft	0.38	10^{-3} cm/s	?	two 60 ft^2 areas
VALLEY MANUFACTURING	5 - 12 ft of sand over 5 - 10 ft of clay over glacial till	27-52 ft	?	permeable to impermeable	perched water	?
INDUSTRIAL TANK FARM	40 - 210 ft clayey silts 900 ft limestone	300 ft	?	very permeable	?	4,400,000 cu yds
TIME OIL COMPANY	sand and gravel with some silt	>30 ft	?	$3x10^{-3}$ cm/s	?	30,000 sq
SOLVENTS STORAGE TANK	unknown	85 ft	?	?	?	unknown
TCAAP PILOT 1	4 - 6 ft sand and loamy sand fill over stained low permeability sediments over sand	170 ft	?	very permeable	?	3800 to 33000 cu yds
TCAAP PILOT 2	same as Pilot 1	"	?	"	?	"
TCAAP SITE D	same as Pilot 1	"	?	"	?	"
TCAAP SITE G	up to 135 ft sand over glacial till and sand	130 ft	?	very permeable	?	?
GAS STATION	6 - 12 ft clayey soil grading to silt & sand	8-10 ft	?	impermeable?	?	?
UNION 76 GAS STATION	18 - 21 ft clayey sand over 5-13 ft gumbo clay over 28-42 ft silty sand over limestone	48-53 ft	?	?	?	unknown
SOUTH PACIFIC RAILROAD	20 - 25 ft silt & sand, gravel layers, 50 ft silty clay @ 40 ft	240 ft	0.1 - 0.3	10^{-4} cm/s	2 - 5%	60 x 70 ft
CUSTOM PRODUCTS	30 ft of fine sand	30 ft	?	?	?	50 acres
ELECTRONIC MANUFACTURING	alluvial clayey silts and sands	90 ft	?	relatively impervious	?	?
PAINT STORAGE	sandy soil with clay strata sands and gravels	40-50 ft	?	?	?	?
THOMAS SOLVENT COMPANY	a sand and gravel alluvial deposit over sandstone	22 ft	?	sand - 0.1 cm/s bedrock- 0.06 cm/s	?	?
HILL AFB VERTICAL VENTS	4 ft silty sand underlain by 16 - 31 ft of sand underlain by discontinuous sand and clay layers	600 ft	?	permeable to impermeable	perched water	90 x 14 ft
HILL AFB LATERAL SYSTEM		"	?	"	"	"
HILL AFB SOIL PILE	mixture of sand and silty sand	"	?	permeable	?	?

? -- no information
GWT -- groundwater table

installed in soils with a wide range of permeabilities. The range of areas and volumes of soil vented by vapor extraction systems is large. Soil vapor extraction systems have been used in shallow as well as deep unsaturated zones. Much of the information needed to fully assess the effects of soil properties (moisture content, organic carbon content, and porosity) on vapor extraction is not available.

As the permeability of the soil decreases, more time is required for extraction and decontamination. In addition to permeability, the presence of heterogeneities make it more difficult to position inlet and extraction wells. The effect of clay lens at the Groveland site resulted in perched water table. During high rainfall periods, the contaminant seeped over the lip of this clay lens and spread further. Extraction wells had to be installed below this clay lens to assure an effective extraction operation. Varying strata was also a concern at the gas station site in Florida (Camp, Dresser, and McKee, 1987). Some layering of soil can make it easier to extract VOCs from soils where air channeling occurs through sand layers with subsequent VOC diffusion from less permeable layers.

The soil moisture content or degree of saturation is also important in that it is easier to draw air through drier soils. A case in point is that of the South Pacific Transportation site in Arizona where the soil was relatively dry (Johnson, 1988; Johnson and Sterrett, 1988). The moisture content was only 2 to 5 percent. After seven months, 6500 kg of dichloropropene had been extracted using a moderate air flow rate of 85 to 250 cfm. Higher air flow rates tend to increase vapor removal because the radius of influence increases and more air is forced through the air filled pores. In addition, more air is pulled through the soil in a shorter time period.

Types and Magnitude of Contamination

The types and magnitude of chemical contamination encountered at the various sites are summarized in Table 8. The common chemical contaminants extracted were trichloroethylene, 1,1,1-trichloroethane, methylene chloride, carbon tetrachloride, tetrachloroethylene, dichloroethylene, toluene, 1,3-dichloropropene, and gasoline along with its constituents (benzene, toluene, ethylbenzene, and xylene). Most chemicals that have been successfully extracted have a low molecular weight and high volatility. Another common screening tool is the air-water partitioning coefficient, expressed in dimensionless terms as Henry's Law constant (See Table 9). Most of the compounds have values of Henry's Law constants greater than 0.01. Vapor extraction can be used to remove large quantities of volatile chemicals as demonstrated at several sites.

EXTRACTION SYSTEM OPERATION

At most sites, the initial VOC recovery rates were relatively high and then decreased asymptotically to zero with time (Oster and Wenck, 1988; Payne *et al.*, 1985; Payne and Lisiecki, 1988; Terra Vac, 1987b). Vapor extraction is more effective at those sites where the more volatile chemicals are still present than when the spill is relatively recent. Several studies have

TABLE 8. PILOT AND FIELD SOIL VAPOR EXTRACTION SYSTEMS -- TYPES AND MAGNITUDE OF CONTAMINATION

SITE	CHEMICALS IDENTIFIED	SPILL VOLUME	INITIAL CONTAMINATION LEVELS	FINAL CONTAMINATION LEVELS	AMOUNT EXTRACTED
FUEL MARKETING TERMINAL	gasoline hydrocarbons	>100000 gal	1.6 ft product on GWT 60-110 ppmv @ 16 ft, 3500-28000 @ 20 ft, 11000-51000 @ 21 ft	?	190 gallons
VALLEY MANUFACTURING	TCE, PCE, MC DCE, TCA	unknown	max concs: 2500mgTCE/kg 40 mgPCE/kg, 12 mgDCE/kg	being measured	being measured
INDUSTRIAL TANK FARM	carbon tetrachloride	200,000 lbs	70% of carbon tet contained in unsat. zone	? initial rate = 250 lb/day	>70% of spill volume
TIME OIL COMPANY	TCE, PCE, TTCA MC, TCA, DCE	unknown	from 5 ppm at 30 ft to over 1000 ppm at 6 in	current status unknown	240 lbs
SOLVENTS STORAGE TANK	TCA, TCE DCA, DCE	unknown	>10 $mgTCA/m^3$, 1 $mgTCE/m^3$	unknown, extraction rate decreased with time	11lb/day
TCAAP PILOT 1	TCE, TCA DCE, toluene + others	unknown	5 - 50 mgVOC/kg stained sediments 4-40 ft BLS TCE up to 8000 mg/kg	not determined	~1000 lbs
TCAAP PILOT 2	"	"	"	"	?
TCAAP SITE D	"	"	"	"	>84,000 lbs VOCs
TCAAP SITE G	TCE, TCA DCE, toluene + others	unknown	>1000 mgVOC/kg	not determined	>85,000 lbs VOCs
GAS STATION	gasoline	unknown	up to 10 in of gasoline on GWT, no HC @ 18 ft BLS	no free product 98% reduction of HC in GW	1200 lbs of gasoline
UNION 76 GAS STATION	benzene, toluene xylene, HCs	unknown	0.2 to 12.4 mgBTEX/kg highest conc. at 15 ft		22,000 lbs in 123 days
SOUTH PACIFIC RAILROAD	dichloropropene	150,000 lbs	30 to 60% of initial spill remaining in soil	less than 10 ppm in 40 soil samples	90,000 lbs
CUSTOM PRODUCTS	PCE	<5000 cu yd soil	8 to 5600 mgPCE/kg soil 92000 mg/m^3 in exhaust	17 ugPCE/kg soil after 280 d	62 - 76 kg in 35 days
ELECTRONIC MANUFACTURING	TCA chl. solvents	unknown	2000 ppmv organics in initial extracted gas	50 ppmv in exhaust (target is 20 ppmv)	>12000 lbs VOCs
PAINT STORAGE	acetone, ketones toluene, xylenes	over 400,000 cu yds soil	Total VOC in GW from 1 to 620,000 ug/L	Total VOC in GW from not detected to 10 ug/L	>7800 lbs after 165 days
THOMAS SOLVENT COMPANY	PCE, TCE, TCA	?	1700 lbs VOC in 1984	not determined	?
HILL AFB VERTICAL VENTS	jet fuel (JP4)	>25,000 gal total	up to 6200 mg/kg fuel in upper 5 ft of soil 200 - 900 mg/kg between 5 - 10 ft deep below detection below 50 ft deep	system not yet operational	1600 lbs in one-well vent test
HILL AFB LATERAL SYSTEM	"	"			
HILL AFB SOIL PILE	"	"	soil vapor conc. up to 80000 ppb in top 10 ft		

BTEX -- benzene, toluene, ethylbenzene, and xylene
DCA -- dichloroethane
DCE -- dichloroethene
HC -- hydrocarbon
MC -- methylene chloride
PCE -- tetrachlorethene (perchloroethylene)

TCA -- trichloroethane
TCE -- trichloroethene
TTCA -- tetrachloroethane
VOC -- volatile organic chemical
na -- not applicable
ppmv -- parts per million by volume

TABLE 9. DIMENSIONLESS HENRY'S LAW CONSTANTS FOR TYPICAL ORGANIC COMPOUNDS.

Component	10^oC	15^oC	20^oC	25^oC	30^oC
nonane	17.21519	20.97643	13.80119	16.92131	18.69235
n-hexane	10.24304	17.46626	36.70619	31.39026	62.70981
2-methylpentane	29.99747	29.35008	26.31372	33.72000	34.08841
cyclohexane	4.43291	5.32869	5.81978	7.23447	8.96429
chlorobenzene	0.10501	0.11884	0.14175	0.14714	0.19014
1,2-dichlorobenzene	0.07015	0.06048	0.06984	0.06417	0.09527
1,3-dichlorobenzene	0.09511	0.09769	0.12222	0.11649	0.16964
1,4-dichlorobenzene	0.09124	0.09177	0.10767	0.12957	0.15637
o-xylene	0.12266	0.15267	0.19704	0.19905	0.25164
p-xylene	0.18076	0.20427	0.26813	0.30409	0.37988
m-xylene	0.17689	0.20976	0.24859	0.30409	0.35656
propylbenzene	0.24446	0.30915	0.36623	0.44143	0.55072
ethylbenzene	0.14030	0.19073	0.24983	0.32208	0.42209
toluene	0.16397	0.20807	0.23071	0.26240	0.32480
benzene	0.14203	0.16409	0.18790	0.21581	0.28943
methyl ethylbenzene	0.15106	0.17762	0.20910	0.22807	0.30953
1,1-dichloroethane	0.15838	0.19200	0.23404	0.25545	0.31194
1,2-dichloroethane	0.05035	0.05498	0.06111	0.05763	0.06995
1,1,1-trichloroethane	0.41532	0.48635	0.60692	0.71119	0.84819
1,1,2-trichloroethane	0.01678	0.02664	0.03076	0.03719	0.05346
cis-1,2-dichloroethylene	0.11620	0.13787	0.14965	0.18556	0.23114
trans-1,2-dichloroethylene	0.25390	0.29815	0.35625	0.38625	0.48640
tetrachloroethylene	0.36410	0.46943	0.58614	0.69892	0.98487
trichloroethylene	0.23154	0.28208	0.35002	0.41690	0.51454
tetralin	0.03228	0.04441	0.05654	0.07643	0.10773
decalin	3.01266	3.53977	4.40641	4.78211	7.99952
vinyl chloride	0.64557	0.71049	0.90207	1.08313	1.12556
chloroethane	0.32666	0.40515	0.45727	0.49456	0.57484
hexachloroethane	0.25522	0.23641	0.24568	0.34129	0.41405
carbon tetrachloride	0.63696	0.80776	0.96442	1.20575	1.51951
1,3,5-trimethylbenzene	0.17344	0.19454	0.23736	0.27507	0.38711
ethylene dibromide	0.01291	0.02030	0.02536	0.02657	0.03216
1,1-dichloroethylene	0.66278	0.85851	0.90622	1.05860	1.27832
methylene chloride	0.06025	0.07147	0.10143	0.12098	0.14512
chloroform	0.07403	0.09854	0.13801	0.17207	0.22270
1,1,2,2-tetrachloroethane	0.01420	0.00846	0.03035	0.01022	0.02814
1,2-dichloropropane	0.05251	0.05329	0.07898	0.14592	0.11497
dibromochloromethane	0.01635	0.01903	0.04282	0.04823	0.06110
1,2,4-trichlorobenzene	0.05552	0.04441	0.07607	0.07848	0.11939
2,4-dimethylphenol	0.35678	0.28504	0.41986	0.20150	0.15074
1,1,2-trichlorotrifluoroethane	6.62785	9.09260	10.18462	13.03840	12.90375
methyl ethyl ketone	0.01205	0.01649	0.00790	0.00531	0.00442
methyl isobutyl ketone	0.02841	0.01565	0.01206	0.01594	0.02734
methyl cellosolve	1.89798	1.53517	4.82210	1.26297	1.53277
trichlorofluoromethane	2.30684	2.87580	3.34222	4.12815	4.90423

Adapted from Howe et al. (1986)

indicated that intermittent venting from individual wells is probably more efficient in terms of mass of VOC extracted per unit of energy expended (Crow *et al.*, 1987; Oster and Wenck, 1988; Payne and Lisiecki, 1988). This is especially true when extracting from soils where mass transfer is limited by diffusion out of immobile air and water. Optimal operation of a soil vapor extraction system may involve taking individual wells in and out of service to allow time for liquid and gas diffusion and to change air flow patterns in the region being vented. Little work has been done to study this.

One of the major problems in the operation of a soil vapor extraction system is determining when the site is sufficiently clean to cease operation. Mass balances using initial and final soil borings have not been particularly successful in predicting the amount of chemical actually removed in a system (Anastos *et al.*, 1985; Camp, Dresser, and McKee, 1988). Soil vapor measurements in conjunction with soil boring and groundwater monitoring may be useful in determining the amount of chemical remaining in the soil. Risk analysis has been used to evaluate final clean up in at least one system (Ellgas and Marachi, 1988). Payne and Lisiecki (1988) suggest intermittent operation near the end of clean up. If there ceases to be a significant increase in vapor concentration upon restart, one can assume the site has been decontaminated.

Malot and Wood (1985) discuss use of *in-situ* soil air extraction in conjunction with groundwater pumping and treatment as a low-cost alternative for the clean up of petroleum and solvent spills. Large quantities of organic chemicals can be retained in the vadose zone by capillary forces, dissolution in soil water, volatilization, and sorption. If this product can be removed before it reaches the groundwater then the problem is mitigated. Since vapor transport is diffusion-controlled in the absence of air extraction, the vapor spreads horizontally, and a concentration gradient is established in the vertical direction as vapor diffuses back to the surface. Malot and Wood (1985) indicate that vapor extraction is effective in removing organic chemical vapor, sorbed chemical, and free product at the water table. This suggests that the soil should be decontaminated by vapor extraction before groundwater clean up can be completed. Vapor extraction becomes more cost-effective as the depth to groundwater increases, primarily because the cost of excavation becomes prohibitive.

The design and operation of soil vapor extraction systems can be quite flexible, allowing for changes to be made during the course of operation, with regard to well placement or blower size, and air flows from individual wells. If the system is not operating effectively, changes in the well placement or the capping the surface may improve it. At one site, the blowers were housed in modules with quick disconnect attachments. This allowed for portability, thus improving the removal efficiency by allowing for the blowers to be moved about the site to particular locations where extraction was required the most.

SECTION 4

CONCLUSIONS

Based on the current state of the technology of soil vapor extraction systems, the following conclusions can be made.

1. Soil vapor extraction can be effectively used for removing a wide range of volatile chemicals over a wide range of conditions.

2. The design and operation of these systems is flexible enough to allow for rapid changes in operation, thus, optimizing the removal of chemicals.

3. Intermittent blower operation is probably more efficient in terms of removing the most chemical with the least energy, especially in systems where chemical transport is limited by diffusion through air or water.

4. Volatile chemicals can be extracted from clays and silts but at a slower rate. Intermittent operation is certainly more efficient under these conditions.

5. Air injection and capping a site have the advantage of controlling air movement, but injection systems need to be carefully designed.

6. Extraction wells are usually screened from a depth of from 5 to 10 below the surface to the groundwater table. For thick zones of unsaturation, maximum screen lengths of 20 to 30 feet are specified.

7. Air/water separators are simple to construct and should probably be installed in every system.

8. Installation of a cap over the area to be vented reduces the chance of extracting water and extends the path that air follows from the ground surface, thereby increasing the volume of soil treated.

9. Incremental installation of wells, while probably more expensive, allows for a greater degree of freedom in design. Modular construction, where the most contaminated zones are vented first, is preferable.

10. Use of soil vapor probes in conjunction with soil borings to assess final clean up is less expensive than use of soil borings alone. It is usually impossible to do a complete materials balance on a given site because most sites have an unknown amount of VOC on the soil and in the groundwater.

11. Soil vapor extraction systems are usually only part of a site remediation system.

12. While a number of variables intuitively affect the rate of chemical extraction, no extensive study to correlate variables to extraction rates has been identified.

SECTION 5

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APPENDIX

SOIL VAPOR EXTRACTION SYSTEMS
SITE DATA SUMMARIES

FILE NAME	SITE
API.SHT	Petroleum Fuels Marketing Terminal, Granger, IN
AWARE.SHT	AWARE Laboratory Study
BELLVIEW.SHT	Union 76 Station, Bellview, FL
BENSON.SHT	Southern Pacific Chemical Spill, Benson, AZ
CLARA.SHT	Electronics Firm, Santa Clara Valley, CA
CUPER.SHT	Leaking Spent Solvents Storage Tank, Cupertino, CA
DAYTON.SHT	Paint Storage Warehouse, Dayton, OH
GASSTA.SHT	Gasoline Station, Unknown Location
GROVE.SHT	Valley Manufactured Products, Groveland, MA
HILL.SHT	Hill Air Force Base, UT
SANJUAN.SHT	Industrial Tank Farm, San Juan, PR
STEVEN.SHT	Custom Products, Stevensville, MI
TACOMA.SHT	Time Oil Company, Tacoma, WA
TCAAP.SHT	Twin Cities Army Ammunition Plant, New Brighton, MN
TRI.SHT	Texas Research Institute Laboratory Study
TYSON.SHT	Tysons Lagoon, PA
VERONA.SHT	Verona Well Field, Battle Creek, MI

ASSESSMENT OF PILOT-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Petroleum Fuels Marketing Terminal, Granger, IN

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Location of Work/Study: A Petroleum Fuels Marketing Terminal located in Granger, Indiana.

Nature of Contamination: In 1980, a valve rupture caused the loss of approximately 100,000 gallons of gasoline. Much of the lost gasoline was recovered using conventional liquid recovery techniques. The remaining gasoline had migrated to the shallow ground water surface at a depth of approximately 25 feet. This floating hydrocarbon layer had a thickness of approximately 1.6 feet in the center of the test cell and extended out beyond the venting cells. Baseline hydrocarbon vapor concentrations measured at a depth of 16 feet, varied between 58 and 113 parts per million by volume (ppmv). At depths between 20 and 20.5 feet, the hydrocarbon vapor concentrations varied between 3450 and 28,000 ppmv. The soil hydrocarbon vapors were most concentrated at a depth of 21 feet (1 foot above the capillary zone). Between depths of 21 to 21.5 feet, the hydrocarbon vapor concentrations varied from 11,000 to 51,500 ppmv.

(33)

Soil/Site Conditions: The soil was quite porous, moderately permeable, and conducive for evaluating the effectiveness of subsurface venting for eliminating hydrocarbon vapors in soil. Average soil porosity was 38% and the average soil permeability was 9.8 x 10^{-4}cm/sec. The soil consisted of sand and fine sand fractions with some traces of silt and clay interspersed with traces of coarse gravel.

Experimental/System Design: The soil vapor extraction system consisted of air inlet and extraction wells; a plastic membrane cap; 2 vacuum pumps; various plumbing, valves, gauges, sampling ports, and probes; and monitoring wells. Two parallel test cells with identical dimensions were located approximately 100 yards southwest of the spill site (See Figure 1). The venting system was installed in a rectangular area, 110′ x 60′. Each test cell contained one vapor recovery well (VRW) positioned between 2 air inlet wells (AIW) in a straight line (Figures 2 and 3) with the distance between first AIW and VRW equal to 20 feet and distance between the second AIW and VRW equal to 40 feet. Each cell contained 16 vapor sampling probes which were installed at depths that varied from 16 to 21.5 feet. The vapor probes were used to obtain discrete samples in the vadose zone at heights ranging from 0.5 to 5 feet above the capillary fringe, which was at a depth 20 feet. A groundwater observation well was drilled to a depth of 35 feet and located midway between the 2 Test Cells. This observation well was used to measure the depth to the hydrocarbon product and the GWT, which was at 24.6 feet. Thermocouples attached to the well casing were used to measure soil temperatures at depths of 16, 20, and 21 feet. Three additional vapor monitoring probes were installed midway between the 2 cells at 13, 20, and 21 feet to monitor the potential influence of each of the cells on the other. The vapor recovery and air inlet wells were constructed of 2-inch PVC casing from the surface to 14 feet below the land surface. A screened interval from 14 to 20 feet in each AIW and VRW consisted of 0.010 inch slotted PVC well casing. The bottom of each well screen was fitted with a solid cap.

The the vapor recovery and air inlet wells were designed to promote lateral flow of air and vapors through the unsaturated zone. Thus, depths typical of basements, substructures, and utility vaults could be simulated, and the control of vapors studied. In order to minimize rainfall infiltration, simulate a surface structure, and insure that the air inlet wells were the primary sources of atmospheric air, the two test cells were covered with a plastic membrane.

Two liquid ring pumps were used as the vacuum source during venting (Figure 4). Both pumps required circulating water to provide a liquid seal. This reduced the possibility of vapor ignition due to sparks (because there were no metal-metal contacts). During operation, the suction side of the pump was connected to the vapor recovery well by a 2-inch PVC pipe. A standard pitot tube was installed between the wellhead and a vacuum control valve to measure the air flow rate. A septum port located on the vapor recovery well exhaust line was used to collect vapor samples from each recovery well. Vapor treatment was not required because of the relatively small quantities of hydrocarbons being released to the atmosphere.

Site Monitoring: The following parameters were monitored on a periodic basis:

- Hydrocarbon concentration and composition from the vapor recovery well exhaust
- Soil vapor concentration and composition at discrete depths and distances from vapor recovery well and air inlet wells
- Volumetric flow rates at each vapor recovery and air inlet well
- Static vacuum measurements at each vapor sampling probe and vapor recovery well
- Physical characterization of soil core samples
    - a) porosity
    - b) soil moisture
    - c) permeability
    - d) pH
    - e) conductivity
    - f) particle size distribution
- Soil temperatures at three soil depths
- Environmental parameters (rain, temperature, barometric pressure)
- Liquid hydrocarbon layer thickness and depth to GWT in monitoring well

Status of Experiment/Site Clean-up: Three experiments were conducted at different flow rates. During each experiment, only one test cell was vented. For 12 days during the first experiment, cell A was vented continuously with an average flow rate of 22.7 ± 2.0 standard cubic feet per minute (scfm). During the second experiment, a flow rate of 18.5 ± 2.3 scfm was used to vent cell B for ten days. During the third experiment, a higher flow rate of 39.8 ± 1.0 scfm was used to vent cell A again for 15 days. In addition, the air inlet wells to cell A were capped after 10 days to determine if the use of air vents would decrease the system's effectiveness.

The rate of reduction in hydrocarbon vapor concentration was initially high during the first one or two days of venting. The rate then reduced dramatically and became relatively constant. The most dramatic reductions occurred along the lines between the extraction and air inlet wells. The time that elasped between the end of the first experiment (cell A vented at the low flow rate) and the beginning of the third experiment (cell A vented at the high flow rate) was 14 days. At the end of this 14 day rest period, the concentration of hydrocarbons in the soil vapor was measured to determine how much hydrocarbon vapor diffused back to the unsaturated zone. The average concentration was 62% of the original. The time required for the vapor concentrations to return to equilibrium was longer than that required for the reduction of hydrocarbon vapors in each cell. This suggests that intermittent blower operation is more economical than yet as effective as continuous venting. The estimated combined volume of recovered hydrocarbon product during the three experiments was 186 gallons. The cumulative product recovery rates at a depth of 40 feet ranged from 31.2 gallons in cell B (18.5 scfm) to 87.9 gallons in cell A (39.8 scfm). At the 20 to 20.5 feet depth (1 foot above the capillary zone), the soil hydrocarbon vapor reduction was 99.2%.

The radial influence of the applied vacuum was approximately 30 to 40 feet, and it increased with the increase in flow rate. Even though the flow rate increased, however, the product recovery rate did not. Only 9 to 11 percent of the air to the extraction wells came from the air inlet wells. Capping the air inlet wells had no significant effect on the product recovery rate. It might be better to provide more air inlet wells and to use a pulsed venting procedure to improve recovery rates. Overall, this pilot scale system was effective in controlling and recovering hydrocarbon vapors in sand or gravel formations of high porosity and moderate permeability.

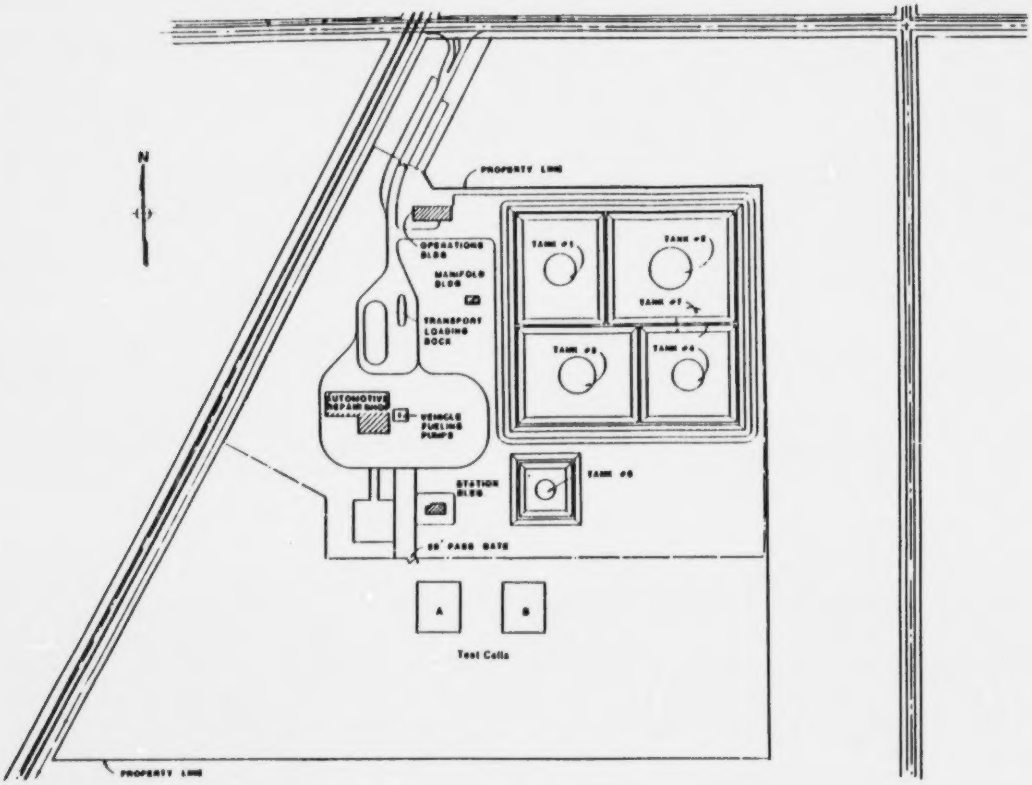
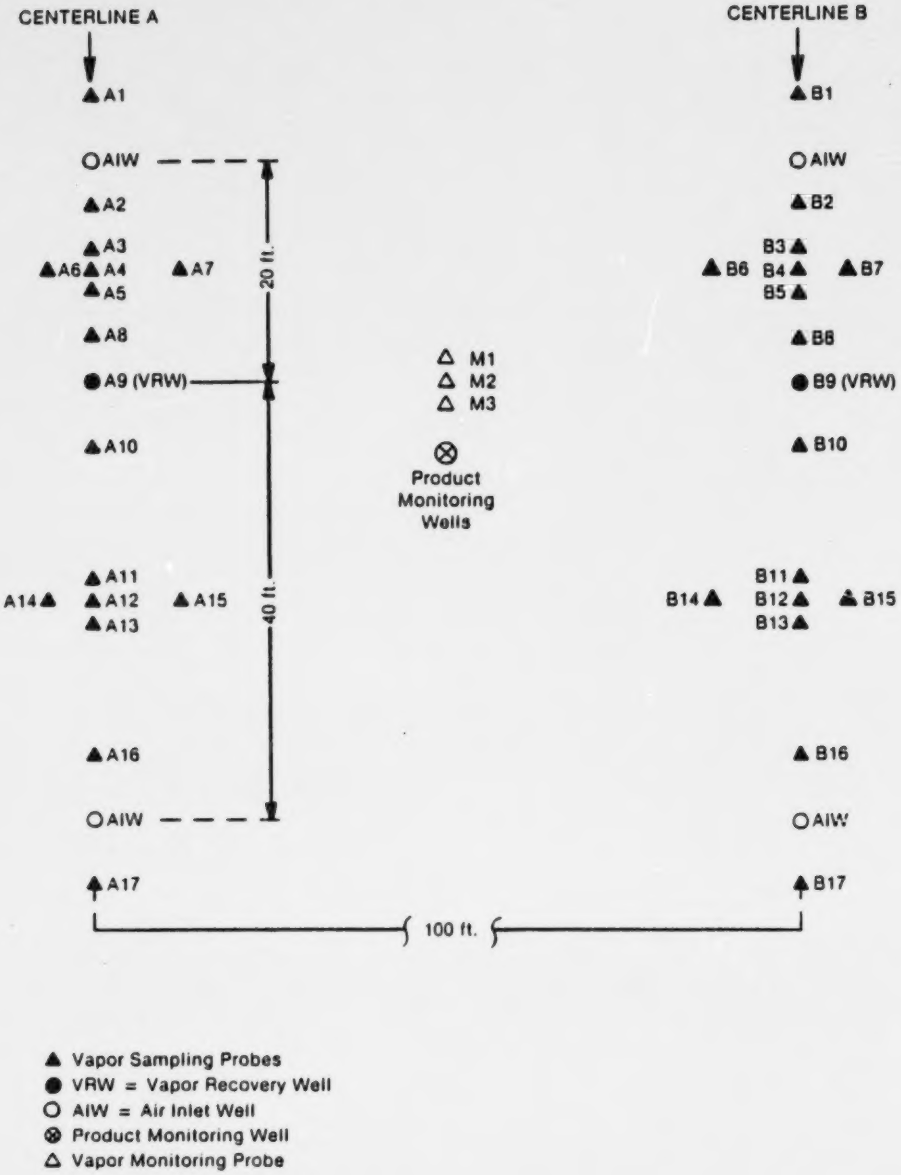

N
PROPERTY LINE
OPERATIONS BLDG
MANIFOLD BLDG
TRANSPORT LOADING DOCK
AUTOMOTIVE REPAIR SHOP
VEHICLE FUELING PUMPS
STATION BLDG
20' PASS GATE
TANK #1
TANK #2
TANK #7
TANK #3
TANK #4
TANK #5
A
B
Test Cells
PROPERTY LINE

Figure 1. Granger Petroleum Fuels Marketing Terminal Site Plan (Source: American Petroleum Institute, 1985).


CENTERLINE A
CENTERLINE B
A1
AIW
A2
A3
A6
A4
A7
A5
A8
A9 (VRW)
A10
A11
A14
A12
A15
A13
A16
AIW
A17
20 ft.
40 ft.
B1
AIW
B2
B3
B6
B4
B7
B5
B8
B9 (VRW)
B10
B11
B14
B12
B15
B13
B16
AIW
B17
M1
M2
M3
Product Monitoring Wells
100 ft.
▲ Vapor Sampling Probes
● VRW = Vapor Recovery Well
○ AIW = Air Inlet Well
⊗ Product Monitoring Well
△ Vapor Monitoring Probe

Probe Depth	Probe Number
13 feet BLS	M1
16 feet BLS	3, 11,
14-20 feet BLS	9
20 feet BLS	1, 2, 4, 6, 7, 8, 10, 12, 14, 15, 16, 17, M2
21 feet BLS	5, 13, M3

Note: M probes were located midway between centerlines A and B.

Figure 2. Venting Configuration for Test Cells A and B, Granger, IN (Source: American Petroleum Institute, 1985).

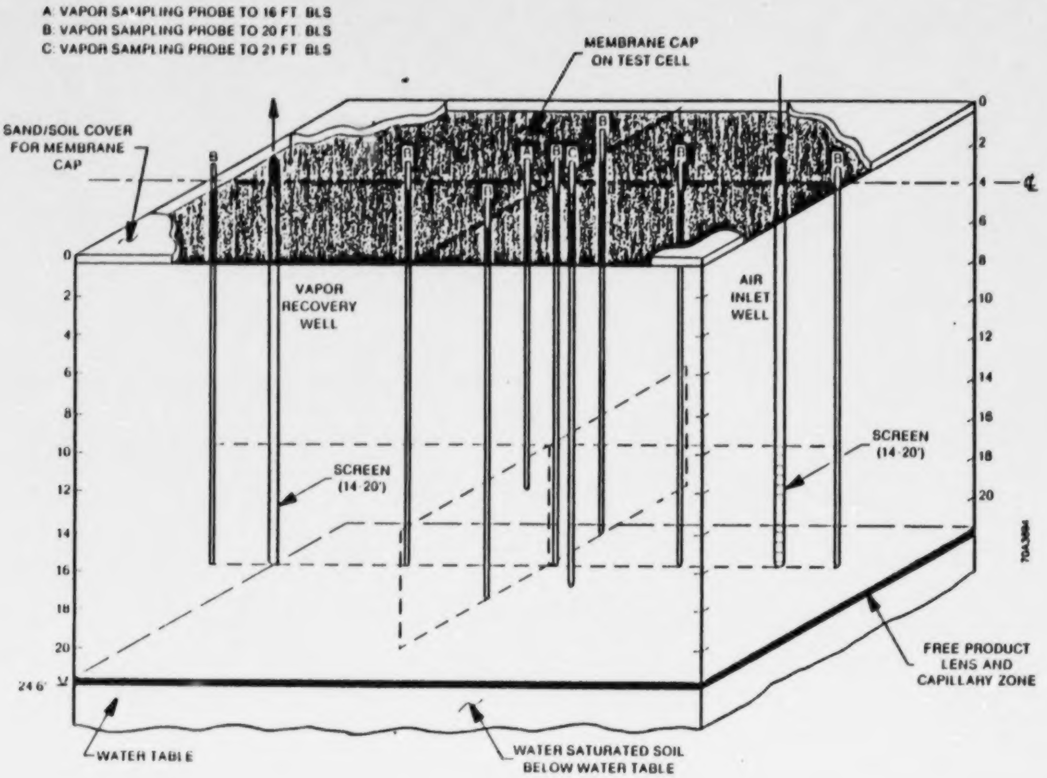

A: VAPOR SAMPLING PROBE TO 16 FT. BLS
B: VAPOR SAMPLING PROBE TO 20 FT. BLS
C: VAPOR SAMPLING PROBE TO 21 FT. BLS
MEMBRANE CAP ON TEST CELL
SAND/SOIL COVER FOR MEMBRANE CAP
VAPOR RECOVERY WELL
AIR INLET WELL
SCREEN (14-20')
SCREEN (14-20')
FREE PRODUCT LENS AND CAPILLARY ZONE
WATER TABLE
WATER SATURATED SOIL BELOW WATER TABLE
24.6'
0
2
4
6
8
10
12
14
16
18
20
22

Figure 3. Cross-section of Subsurface Venting System, Granger, IN (Source: American Petroleum Institute, 1985).

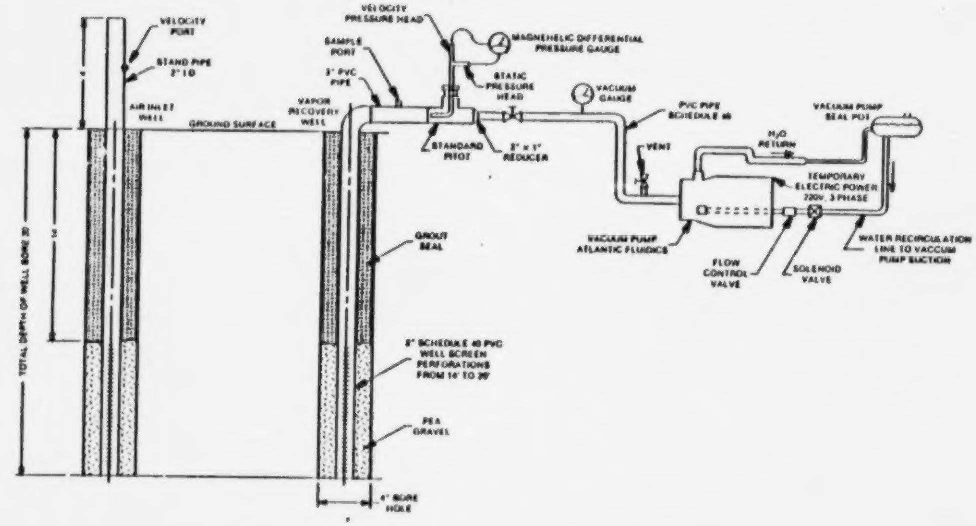

VELOCITY PORT
STAND PIPE 2" I.D.
AIR INLET WELL
GROUND SURFACE
VAPOR RECOVERY WELL
3" PVC PIPE
SAMPLE PORT
VELOCITY PRESSURE HEAD
MAGNEHELIC DIFFERENTIAL PRESSURE GAUGE
STATIC PRESSURE HEAD
STANDARD PITOT
3" x 1" REDUCER
VACUUM GAUGE
PVC PIPE SCHEDULE 40
VENT
H_2O RETURN
VACUUM PUMP SEAL POT
TEMPORARY ELECTRIC POWER 220V, 3 PHASE
VACUUM PUMP ATLANTIC FLUIDICS
FLOW CONTROL VALVE
SOLENOID VALVE
WATER RECIRCULATION LINE TO VACCUM PUMP SUCTION
GROUT SEAL
2" SCHEDULE 40 PVC WELL SCREEN PERFORATIONS FROM 14' TO 20'
PEA GRAVEL
4" BORE HOLE
TOTAL DEPTH OF WELL BORE 20
14

Figure 4. Soil Vapor Extraction System for Granger, IN, Site (Source: American Petroleum Institute, 1985).

ASSESSMENT OF LAB-SCALE VAPOR EXTRACTION SYSTEMS

SUMMARY SHEET

Site/Project Name: AWARE Lab Study

Principal Investigator:
AWARE Incorporated
621 Mainstream Drive
Suite 200, Metro Center
Nashville, TN

Investigative Report:

AWARE, Inc., "Phase I - Zone I Soil Decontamination Through In-Situ Vapor Stripping Processes," (Contract Number 68-02-4446), Final Report, Prepared for: U.S. Environmental Protection Agency, Small Business Innovative Research Program , Washington, D.C. Prepared by: AWARE, Inc., 621 Mainstream Drive, Suite 200, Metro Center, Nashville, TN 37228, April 1987.

Location of Work/Study: AWARE's Nashville Laboratory

Nature of Contamination: Three chemicals were studied

A) Trichloroethene (TCE)
B) Acetone
C) Chlorobenzene

These chemicals were studied as pure chemical and as chemical saturated with water.

Soil/Site Conditions: Each chemical was studied on 2 soils:

A) Western Tennessee Loess
B) New Jersey Cohansey Sand

Two laboratory columns were used in parallel for this study with each packed with one of the soils. Figure 1 shows the column setup.

Experimental/System Design: This VES lab study set-up consisted of two glass soil columns (with intake and exit ports); a dual vacuum pump; two flow meters; a humidifying flask; and various valves, sensors, sampling ports and plumbing. The vapor stripping equipment was designed to allow for continuous parallel operation of both soil columns. A Cole-Parmer aspirator pump with dual vacuum sources was used to induce a steady air flow through each column. Flowrates ranged from 4 to 6 mL/min. A water flask was attached to the inlet gas end of the column to provide saturated air. System plumbing allowed for flow measurement and air sampling of the column exit gases. The air sampling ports were designed to allow insertion of Supelco volatile organics purge traps so that direct thermal desorption and gas chromatography analysis of the stripped volatile organic contaminants could be used.

All organic concentrations were measured using either methanol extraction of the soil or desorption of adsorbed vapor from Supelco multiphase traps. Analyses were performed on a Tracor Model 560 gas chromatograph using a Hall detector with an overall system detection limit of 5 nanograms of chemical.

Status of Experiment/Site Clean-up: A total of five experiments were performed. Each experiment contained three major procedures. The first procedure consisted of spiking the soil and then performing an analysis of the companion columns (Note: A companion column is a simple glass column with a screen covered glass support for the soil and bottom drain tube. The height-to-diameter ratio was the same as used in the parallel primary stripping columns. There was one companion column for each primary stripping column. These companion columns were spiked and then drained in the same way as the parallel primary stripping columns. Immediately after stripping was initiated, these companion columns were sacrificed and the soil was analyzed to determine the initial concentrations in the primary stripping columns. Therefore, the primary columns remained undisturbed until the stripping test period was completed. During the stripping period, the second major procedure of air sampling was performed on the parallel primary columns. At the end of the test period, the last major procedure consisted of performing the final soil analysis of each primary column run was completed.

EXPERIMENT 1: Cohansey Sands and TCE

The duration of the experiment was four weeks. Column 1 was spiked with pure TCE and Column 2 was spiked with TCE saturated with water. The initial conditions were as follows:

	Column 1	Column 2
% Moisture	4.1	17.4
% Volatiles	0.3	0.3
TCE Conc. (ug/gm)	8,850	15

The residual chemicals (those chemicals that remain in the soil after spiking/draining and later after the experiment is completed) from the pure TCE spike resulted in higher soil concentrations and higher air concentrations (often outside the quantifiable range). Based on residual soil concentrations (the amount of chemical still remaining after the experiment was completed and the soil analyzed), TCE removal from the soil columns was excellent both in the absence and presence of water, 99% and 94%, respectively, over the 4 week period.

The volatiles purge trap apparently developed defects upon excessive handling so difficulty existed in obtaining reproducible results. Compaction of the adsorbent and gas-flow short circuiting also lead to sampling error. In addition, early in the run the exit air concentrations were frequently high enough to exceed the quantifiable range of the GC or the trap. Thus, more credibility should be afforded to the initial and final bulk soil residue analysis. It is important to point out that Aware then reduced the sampling periods to the shortest duration which allowed for reproducible procedures or that two different sampling times (15 and 60 seconds) were used for each sample in order to bracket a usable result.

EXPERIMENT 2: Western Tennessee Loess and TCE

The initial conditions were as follows:

	Column 1	Column 2
% Moisture	10.2	24.4
% Volatiles	0.28	0.24
TCE Conc. (ug/gm)	4,010	4.2

As in the experiment 1, a significantly higher TCE residue remained in the column spiked with pure TCE. However, the removal rate was still ten times higher than the water/TCE system at the experiment's termination (a similar situation existed in the first experiment).

		Ave. Removal Rate	Specific Removal Rate
Experiment 1	Column 1	2,349 ug TCE/day	0.9 ug TCE/gm Air-day
	Column 2	31 ug TCE/day	0.012 ug TCE/gm Air-day
Experiment 2	Column 1	22,478 ug TCE/day	9.0 ug TCE/gm Air-day
	Column 2	2,349 ug TCE/day	0.9 ug TCE/gm Air-day

This experiment was terminated after 1 month. The column spiked with pure TCE again exhibited a higher air concentration. Therefore, the average removal rate was higher. Excellent removal was evidenced in the column which was spiked with pure TCE. The data from the water saturated system requires further interpretation, since the data from column 2 are suspect.

EXPERIMENT 3: New Jersey Cohansey Sands and 50/50% V/V Acetone/Water

This experiment was run in duplicate to assess reproducibility. The initial conditions were as follows:

	Column 1	Column 2
% Moisture	14.6	12.6
% Volatiles	0.3	0.28
Acetone Conc. (ug/gm)	43,350	46,050

For column 1, the final soil analysis revealed 97% removal. However, the data from Column 2 data are suspect.

EXPERIMENT 4: Western Tennessee Loess and 50/50% V/V Acetone/Water

The initial conditions were as follows:

	Column 1	Column 2
% Moisture	7.73	6.30
% Volatiles	1.05	0.97
Acetone Conc. (ug/gm)	87,450	87,300

Experimental difficulty with the traps for both columns as the experiment progressed, has essentially eliminated data utilization with the exception of the broad statement that Acetone does strip from the soil based on 86 to 99% removal in only 12 days.

EXPERIMENT 5: Pure Chlorobenzene On Both Test Soils

Both soils were run simultaneously for 8 days with the following initial conditions:

	Column 1	Column 2
	(Tennessee Loess)	(Cohansey Sands)
% Moisture	4.4	10.2
% Volatiles	0.38	1.12
Average Chlorobenzene Concentration In Soil	13,000 mg/kg	33,000 mg/kg

The air flow rate ranged from 3.1 mL/min to 5.6 mL/min with an average flow rate of 4.9 mL/min. The residual (weighted bulk average) in loess was 271 mg/kg for a 98% reduction while the sand had a residual of 18,170 mg/kg after eight days for a 45% reduction.

Note: The 60 second sampling period with traps versus the 15 second period provided the more consistent data. The chlorobenzene did not exceed the quantifiable range even at the 60 second sampling interval. The removal data obtained from the traps were essentially the same indicating chlorobenzene removal at the same rate.

Removal rates ranged from 45 to 99% after eight days based on initial bulk and final bulk residual values.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Union 76 Gasoline Station, Bellview, FL

Principal Investigators:

Camp, Dresser, and McKee, Inc.
One Center Plaza
Boston, MA 02108

Terra Vac Corporation
4923 W. Waters Avenue
Tampa, FL 33614

Investigative Reports:

Camp, Dresser, and McKee, Inc., "Interim Report For Field Evaluation of Terra Vac Corrective Action Technology at a Florida Lust Site," Prepared for: U.S. Environmental Protection Agency, Edison, NJ, Contract No. 68-03-3409, Prepared by: Camp, Dresser, and McKee, Inc., One Center Plaza, Boston, MA 02108, December 21, 1987.

Terra Vac Corporation, "Union 76 Gas Station Clean-Up, Bellview, Florida," Tampa, FL, 1987.

Location of Work/Study: Bellview, Florida

Nature of Contamination: Previous investigations directed by the Florida Department of Environmental Regulation (FDER) indicated that an underground storage tank at the Union 76 gas station in Bellview, Florida, was a source of subsurface hydrocarbons. In December 1986, four 6-1/4" soil borings were made at the site, and soil samples were obtained every 2-1/2 feet. The maximum depths sampled were from 52 to 60 feet. In addition, soil samples were obtained with a hand auger at three locations in the storage tank area. All samples were analyzed on-site for gasoline components. Benzene, toluene, ethylbenzene, and xylenes (BTEX) and total volatile hydrocarbons were quantified by gas chromatography. Initial soil concentrations of BTEX were as high as 97 mg/kg, and total hydrocarbons were as high as 230 mg/kg. The highest concentrations of benzene, toluene, and xylene were observed at approximate depths of 10 to 20 feet, above a clay layer and perched water table.

Soil/Site Conditions: The soil borings revealed four distinct stratigraphic zones. Clayey sands were observed from the surface to depths of 18 to 21 feet, where Gumbo (a plastic clay) was encountered. The thickness of this clay layer varied from 5 to 13 feet. Beneath this clay layer, silty sand was observed to depths of 28 to 42 feet below the surface. The silty sand layer was underlain by a weathered limestone which consisted of sand, shells, and cavities in the upper portion. Geologists noted that this limestone layer is probably part of the Upper Eocene Ocala formation. Groundwater was encountered at depths between 48 and 53 feet below the surface, while perched groundwater was observed above the clay layer in wells VE-1, ME-1 and ME-2 (Figure 1).

Experimental/System Design: The soil vapor extraction system consisted of six extraction wells; a vacuum pump; a gas flow meter; various plumbing, valves, gauges, and sampling ports; a gasoline/water separator; and monitoring wells (Figure 2). Pavement, which was already in place, was used as a cap. A vacuum extraction/monitoring well was installed in each borehole (see Figure 2 for locations). The wells, VE-1 and VE-2 were used primarily for subsurface hydrocarbon vacuum extraction. Multi-level, dual purpose wells, which could monitor the subsurface vacuum as well as extract hydrocarbons from two to three hydrogeologic zones, were installed at the other two boreholes (ME-1 and ME-2). Well ME-1, which consisted of three monitoring wells, was capable of monitoring the subsoil at depths of 13, 35 and 50 feet. Well ME-2 consisted of two monitoring wells at depths of 16 and 58 feet. Each of the wells was connected to the vacuum extraction unit by way of a manifold system. So as not to interfere with the continuous operation of the service station, well heads were installed in underground valveboxes, and the vacuum extraction manifold was covered by concrete. The system was modified to include an in-line air/water separator to separate small quantities of gasoline product and water that were being extracted from the subsoils along with the hydrocarbon vapor.

Status of Experiment/Site Clean-up: A pilot test of the vacuum extraction operation started on January 29, 1987. By the end of February 1987, the pilot test results indicated that it was necessary to operate the system continuously in order to estimate the time required for clean-up. Due to power outages and numerous administrative problems (for example, approval of permit to discharge extracted water), the system experienced limited operation during the months of March, April, and May. During June and July, the system was operating on a nearly continuous basis. Initial extraction rates for gasoline hydrocarbons ranged from 295 pounds (39 gallons) per day in VE-1 to 1950 pounds (260 gallons) per day in ME-1-50. During this pilot test, wellhead concentrations decreased with time which would indicate the subsoils were being cleaned up. A total of 22,027 pounds (2937 gallons) of gasoline hydrocarbons had been extracted from the site as of August 1987. An independent evaluation of this system was conducted in September through October 1987 for EPA by Camp, Dresser, and McKee, Inc. Additional soil borings, soil vapor samples, and groundwater samples were collected. During this 25 day evaluation period, 22 additional pounds of BTEX were removed. Taking into account other volatile gasoline components removed, an additional 200 pounds of hydrocarbons were removed. No significant changes in the soil, soil vapor, or groundwater samples were noted.

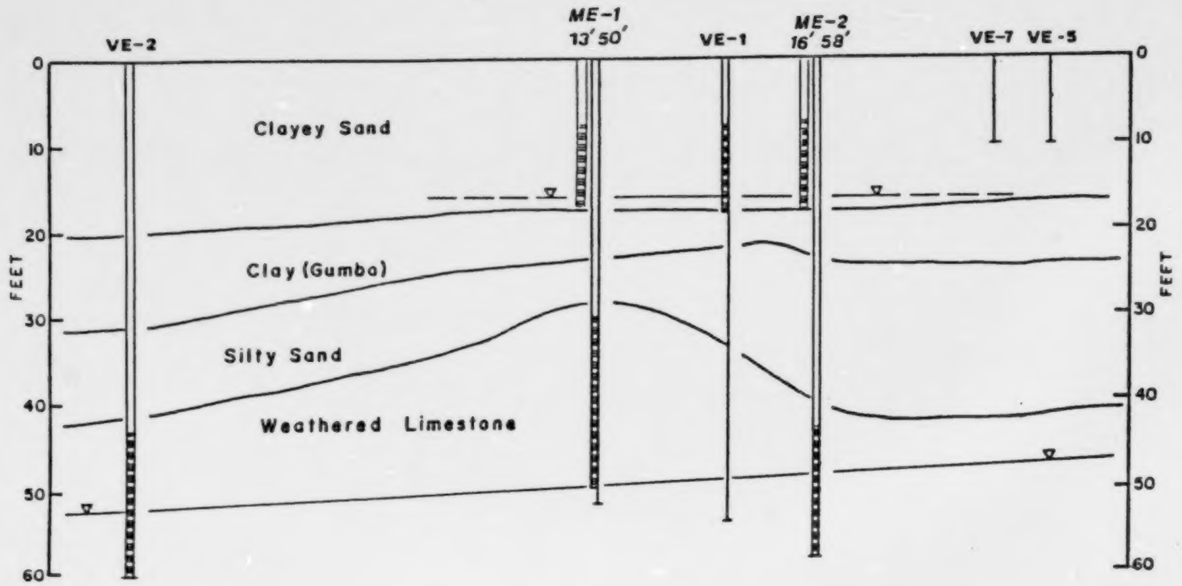

VE-2
ME-1
13' 50'
VE-1
ME-2
16' 58'
VE-7
VE-5
Clayey Sand
Clay (Gumbo)
Silty Sand
Weathered Limestone
FEET
FEET
0
10
20
30
40
50
60

Figure 1. Cross-section of Soil Vapor Extraction System at Bellview, FL (Source: Terra Vac, 1987).

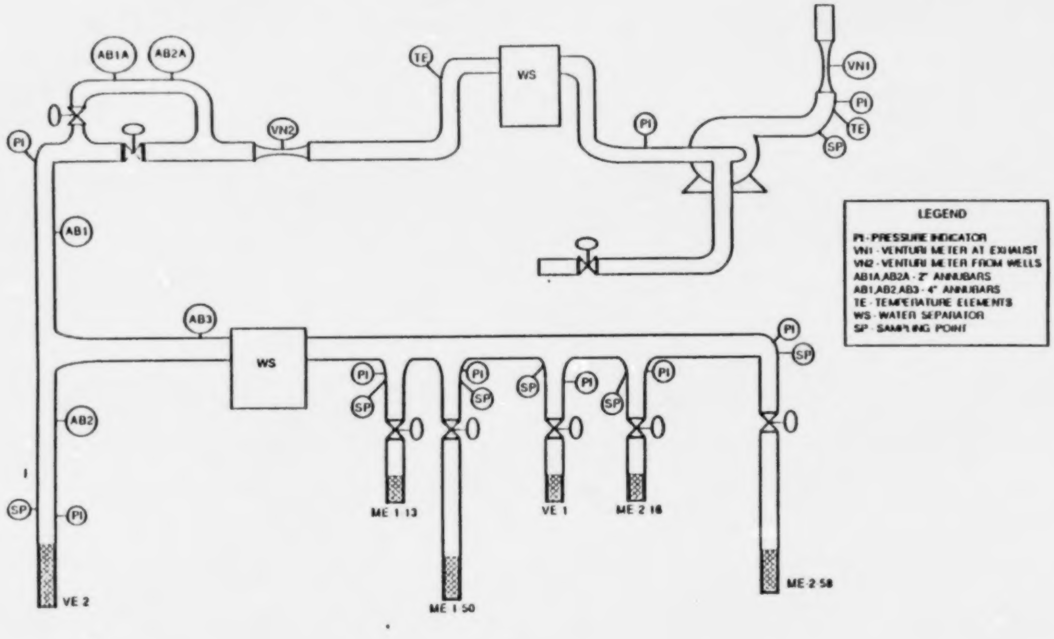

AB1A
AB2A
TE
WS
VN1
PI
TE
SP
VN2
AB1
AB3
AB2
SP
PI
ME 1 13
ME 1 50
VE 1
ME 2 16
ME 2 58
VE 2
LEGEND
PI - PRESSURE INDICATOR
VN1 - VENTURI METER AT EXHAUST
VN2 - VENTURI METER FROM WELLS
AB1A,AB2A - 2" ANNUBARS
AB1,AB2,AB3 - 4" ANNUBARS
TE - TEMPERATURE ELEMENTS
WS - WATER SEPARATOR
SP - SAMPLING POINT

Figure 2. Soil Vapor Extraction System at Bellview, FL (Source: Camp Dresser, and McKee, 1988).

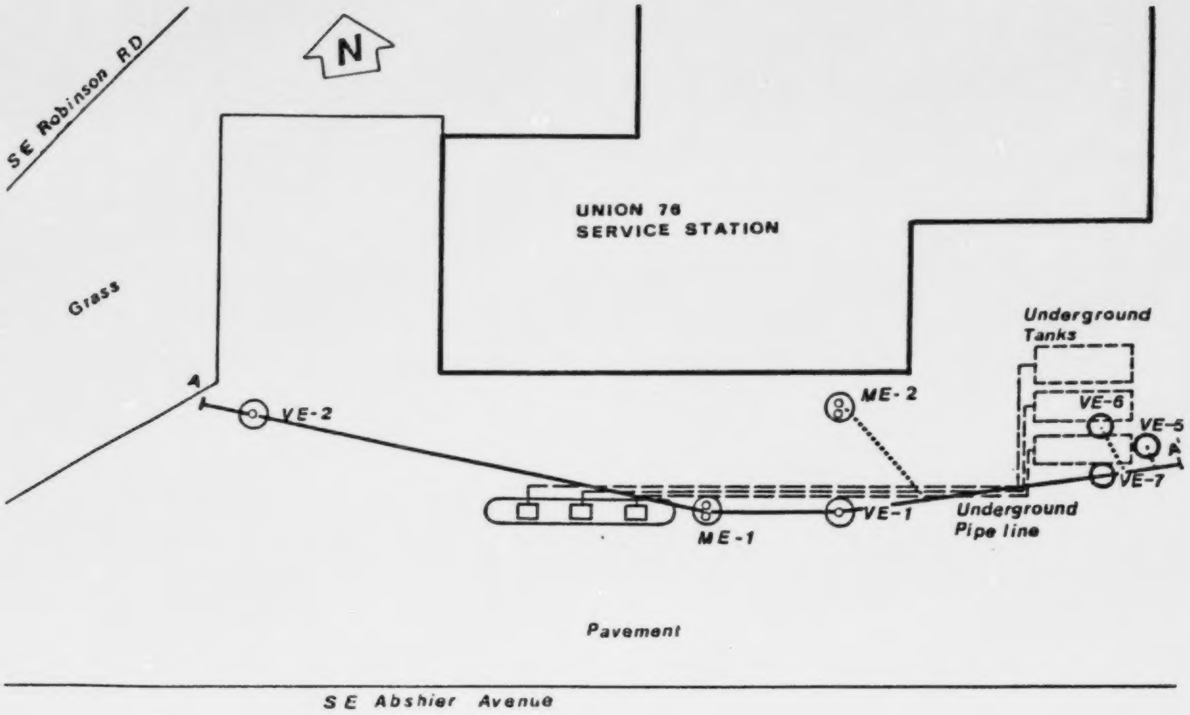

N
SE Robinson RD
UNION 76
SERVICE STATION
Grass
Underground
Tanks
A
VE-2
ME-2
VE-6
VE-5
VE-7
ME-1
VE-1
Underground
Pipe line
Pavement
SE Abshier Avenue

Figure 3. Extraction Well Locations at Bellview, FL (Source: Terra Vac, 1987).

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Southern Pacific Transportation Company spill site near Benson, AZ

Principal Investigators: International Technology Corporation

Jeffrey J. Johnson and R. J. Sterrett
Department of Geological Engineering
Colorado School of Mines

Investigative Reports:

Johnson, J.J., "In-Situ Soil Air Stripping: Analysis of Data From A Project Near Benson, Arizona," M.S. Thesis, Colorado School of Mines, March 16, 1988.

Johnson, J.J., and R.J. Sterrett, "Analysis of In Situ Soil Air Stripping Data," Proceedings of the 5th National Conference on Hazardous Wastes and Hazardous Materials, HMCRI, Las Vegas, NV, April 19-21, 1988.

"Subsurface Investigation and Assessment of Remedial Action Alternatives, Benson Train Derailment", Project No. 846292, International Technology Corporation, San Francisco, CA, 1984.

Location of Work/Study: Three miles east of Benson in Southern Arizona.

Nature of Contamination: On April 8, 1984, a Southern Pacific Transportation Company train derailed three miles east of Benson, AZ. One of the derailed cars contained 1,3-dichloropropene (DCP), a VOC used as a pesticide. Approximately 150,000 pounds of the pesticide leaked into the soil. Approximately 600 cubic yards of the contaminated soil was excavated and piled south of the tracks.

Soil borings revealed that the highest DCP concentration was 54,500 ppm at a depth of 5 feet (approximately 20 feet northwest of the spill). The area of contamination was 60 feet by 70 feet and centered under the railroad tracks. At a depth of 20 feet, the area of contamination decreased to 20 feet by 25 feet. At depths between 20 and 25 feet, the DCP concentrations in the soil were below 10 ppm (which was the EPA established clean-up level). See Figures 1 and 2 for location of soil borings and site cross-section with contamination levels.

It was estimated that approximately 45,000 to 90,000 pounds of the original 150,000 pounds of DCP that had spilled, remained in the soil and the excavated soil pile. Approximately 60,000 to 105,000 gallons of the

DCP had volatilized into the atmosphere.

Soil/Site Conditions: Heavily stratified deposits, that consisted of silty, well graded, medium dense to dense dry sands exist from the ground surface to a depth of about 20 to 25 feet. The overall moisture content ranged from 2 to 5 percent. Occasional gravel layers up to six inches thick were also present. A 50 foot thick silty clay layer was forty feet below the ground surface. This layer was typically dry and hard. The groundwater table was encountered at 240 feet below the ground surface. The soils in the unsaturated zone were nonhomogeneous based on sieve analysis. The mass of particles less than 0.002 mm diameter present ranged from 7 to 29 percent by weight. The average porosity was 30 percent. The average hydraulic conductivity was 10^{-4} cm/sec.

Experimental/System Design: The soil vapor extraction system consisted of 79 extraction wells installed incrementally; 3 separate blower systems; various plumbing, valves, pitot tubes, and monitoring wells. Figures 3 and 4 show the system design and well layout. The extraction wells varied in depth from 15 to 25 feet and most of the wells were installed at angles under the tracks. The wells were made of 2" PVC casing connected to a 2" screen with 0.128 inch slots. The screens extended from a depth of 5 feet to the bottom of the well. Exhaust gas was vented to the atmosphere. The design of the blower systems allowed for alterations or the addition of additional wells. Each extraction well was connected to a 4" PVC manifold header by a 2" PVC pipe. This header was connected to the intake side of the blower. The 3 blowers were operated independently and were connected to different numbers of extraction wells (21 connected to the "north" system, 23 to the "south", and 35 to the "west"). The north blower system was converted to air injection wells toward the end of the project.

The radius of influence extended beyond the contamination area. The lowest static pressure was less than 0.04 inches of mercury, in observation well number 8. On the average, the static pressure from all wells ranged from 0.04 to 0.48 inches of mercury. Air flow rates varied daily from 86 to 250 cfm.

Status of Experiment/Site Clean-up: This system operated continuously for seven months. At the end of February, 1985, 44 soil samples were collected and analyzed. Only four of the samples exceeded 10 ppm DCP, which was the EPA's clean-up criteria. The maximum concentration recorded was 89 ppm. Approximately 6500 kilograms of DCP were extracted from the spill site. Overall, the capital costs for this project were approximately $25,000 and $500,000 was spent for operational costs.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Electronics Manufacturing Facility in Santa Clara Valley, CA

Principal Investigators:
Woodward-Clyde Consultants
One Walnut Creek Center
100 Pringle Avenue
Walnut Creek, CA

Investigative Report:

Bennedsen, M.B., J.P. Scott, and J.D. Hartley, "Use of Vapor Extraction Systems for In Situ Removal of Volatile Organic Compounds from Soil," Proceedings of National Conference on Hazardous Wastes and Hazardous Materials, HMCRI, pp. 92-95, 1985.

Location of Work/Study: Santa Clara Valley, California

Nature of Contamination: Soil was contaminated by a spent solvents storage tank that had been leaking. Several chlorinated solvents were stored in the tank, but an estimated 80% of the total mass of chemical lost was 1,1,1-trichloroethane (TCA). An initial boring beneath the tank revealed a high concentration of solvents at a depth of about 40 feet below the ground surface. Analysis of the gas that was initially extracted showed that it contained over 2000 ppmv of organics. The total mass of solvents lost to the soil was unknown.

Soil/Site Conditions: The soils in the area are predominantly alluvial clayey silts and sands. Overall, the subsurface soil system was judged to be relatively impervious. The GWT was at a depth of about 90 feet.

Experimental/System Design: The soil vapor extraction system consisted of two air inlet and two extraction wells; two blowers; a gas flow meter; and various plumbing, valves, gauges, and sampling ports. Two borings were drilled on opposite sides of the tank location. One of the borings was completed for operation as a vacuum extraction well and the other boring as an air inlet well. Both well casings were 2 inches in diameter. A nearby building was operated under a continuous low vacuum to prevent accumulation of solvent vapors in the work area. A duct to the building ventilation blower was connected to the extraction well. The resulting vacuum created at the well head was about 0.2 inches of mercury, and the gas flow rate from the well was about 10 cubic feet per minute (cfm). A vacuum gauge was connected to the air inlet well and gave a reading of about 0.012 inches of mercury when the well was capped to prevent inflow. These data indicate that the applied vacuum of 0.2 inches of mercury was effective in inducing a flow of air through the soil over a distance of about 30 feet from the extraction well. A dedicated blower assembly was added to the system and the extraction rate was increased to about 100 cfm. An additional extraction well was installed nearer the leak source and was connected to the blower. With both wells in service, a vacuum of about 3 inches of mercury was sufficient to induce a flow rate of 100 cfm through the soil.

Status of Experiment/Site Clean-Up: Approximately 12,000 lb of VOC's were extracted over a period of three years of operation. During that time, the concentration of TCA in the extracted gas decreased from over 2000 to about 50 ppmv. It was expected that this system would remain in operation until the concentration of VOC's in the extracted gas was less than 20 ppmv. Since the system was installed prior to 1985, it is presumed that this site has been cleaned up.

ASSESSMENT OF PILOT-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Spent solvents storage tank in Cupertino, CA

Principal Investigator:
M.B. Bennedsen
Woodward-Clyde Consultants
One Walnut Creek Center
100 Pringle Avenue
Walnut Creek, CA

Investigative Report:

Bennedsen, M.B., "Vacuum VOC's from Soil," Pollution Engineering, Vol. 19(2), pp 66-68, Feb. 1987.

Location of Work/Study: A major electronics firm in Cupertino, CA.

Nature of Contamination: In 1983, it was discovered that a storage tank had leaked. Woodward-Clyde Consultants were hired to perform the site investigation and determine the appropriate remedial measures. During the investigation a vacuum extraction system was installed to test its removal efficiency and to determine the extent of the contamination. A series of laboratory analyzes of the extracted soil gas, performed over the first several months of operation indicated that it typically contained over 10,000 ug/cubic meter of 1,1,1-trichloroethane plus a total of about 1000 ug/cubic meter of other VOCs (trichloroethylene, 1,1-dichloroethylene, and 1,2-dichloroethane.

Soil/Site Conditions: The groundwater table (GWT) at this site is approximately 85 feet below the surface of the ground. No information on the soil or geological conditions was provided

Experimental/System Design: The soil vapor extraction system consisted of air inlet and extraction wells; a blower; a gas flow meter; various plumbing, valves, gauges, and sampling ports; and an air/water separator. One of the required soil borings was completed with a section of perforated well casing above the groundwater table, and a vacuum was applied. On the opposite side of the former tank location, another boring was constructed in a similar fashion but to act as an air inlet well to the contamination zone when the vacuum was applied to the extraction well. Initially, 3-in. diameter, valved PVC pipe was installed connecting the wellhead of the extraction well to a 24-in. diameter duct delivering air to the system's vacuum source. The test site's vacuum source was a building ventilation blower, mounted on the roof of an adjacent building. It operated continuously for several months at an intake vacuum of approximately 0.24 inches of mercury. It pulled approximately 10 cfm of gas from the surrounding soil upon connection to the 3 in. diameter well casing. The system extracted VOCs at a rate of approximately 5 kg/day.

The system's capacity was increased in November 1985 by the addition of a positive displacement blower designed to operate at a vacuum of 6 inches of mercury and produce an extraction rate of approximately 100 cfm. The blower speed and capacity rating could be varied by changing pulley sizes on the belt drive. As installed, the blower had a capacity of about 100 cfm, but the 5 hp electric drive motor selected for the unit was capable of driving the blower at its maximum rated capacity of about 300 cfm. At the same time, the system was connected to additional wells and extended to connect to other wells located in an area where the presence of contamination of the soil had been detected. By January 1986, a stable new operating configuration had been developed. Analysis of the soil gas that was extracted revealed that during this test a progressive decrease in the concentration of the extracted soil gas's VOCs occurred.

The blower assembly included a silencer and a sound absorbing cover because the unit was located in an area where noise levels were of concern. Also, a 55 gallon air-water separator tank was installed ahead of the blower to trap water extracted with the soil gas. Bennedsen (1987) noted that air in soil will normally be nearly saturated with water vapor and that, when the air expands due to the application of a vacuum, the temperature decreases enough to cause condensation. Therefore, the air-water separator is required to protect the blower from the water in the extracted air.

In order to measure the quantity of soil gas extracted, an orifice plate was connected to a U-tube manometer and installed on the blower discharge pipe. The concentration of volatiles in the extracted soil gas were determined by laboratory analysis of samples drawn from a sampling port on the blower discharge line.

Status of Experiment/Site Clean-up: No information on the current status of this site clean-up was available.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Paint Storage Warehouse

Principal Investigators:
Dr. Frederick Payne
Midwest Water Resources, Inc.
Charlotte, MI

Investigative Reports:

Payne, F.C., and J.B. Lisiecki, "Enhanced Volatilization for Removal of Hazardous Waste form Soil," Proceedings of the 5th National Conference on Hazardous Wastes and Hazardous Materials, HMCRI, Las Vegas, NV, April 19-21, 1988.

Site visit made by Dr. Neil J. Hutzler, MTU and Mr. Paul de Percin, EPA Project Officer on December 30, 1987.

Location of Work/Study: Dayton, Ohio

Nature of Contamination: Paint solvents, primarily toluene

Site/Soil Conditions: Sandy soil with clay strata

Experimental/System Design: The soil vapor extraction system consisted of injection and extraction wells; heated headers from extraction wells; 8 blowers; various plumbing, valves, gauges, and sampling ports; an air/water separator; and monitoring wells. Concrete, which was already in place, and a clay cover were used to provide an impermeable cap. Initially, vapor treatment at this site consisted of burning the extracted vapor. Injection and extraction wells were installed in two or three separate geologic strata. The system was installed as four identical modules with 2 blowers each -- one for extraction and one for injection. The installation of modules proceeded from the most contaminated area to those areas with less contamination. The most contaminated area was capped with a clay cover. The remaining area is beneath a concrete floor. Vapor treatment was discontinued when the emission rates decreased to State of Ohio approved levels. Even though most of the contaminated soil is below the concrete slab, the concrete did not act as an impermeable barrier. An air/water separator had to be installed when excessive water was pulled from the soil.

Status of Experiment/Site Clean-up: The site is currently in active treatment stage and should be nearing completion sometime in 1988.

Chronological Sequence of Events:

May 1987 - Paint warehouse fire

June 1987 - Design proposed

July 1987 - First unit installed

December 30, 1987 - Site visit made by Dr. N.J. Hutzler of Michigan Tech and Mr. Paul de Percin of the EPA.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Gasoline Station

Principal Investigators:

James J. Malot
Terra Vac Corporation
356 Fortaleza St.
Box 1591
San Juan, Puerto Rico 00903

Paul R. Wood
Applied Technologies Group
2200 N.E. 124th. Street
North Miami, FL 33181

Investigative Reports:

Malot, J.J., and P.R. Wood, "Low Cost, Site Specific, Total Approach to Decontamination," presented at the Conference on Environmental and Public Health Effects of Soils Contaminated with Petroleum Products, University of Massachusetts, Amherst, MA, October 30-31, 1985.

Visser, M.L., and J.J. Malot, "Removal of Volatile Contaminants from the Vadose Zone of Contaminated Ground," U.S. Patent No. 4,593,760, June 10, 1986.

Location of Work/Study: Unknown

Nature of Contamination: An electrical utility company installed a new manhole and conduit line adjacent to a gasoline station. Company personnel discovered that explosive vapors had penetrated the new conduit system prior to making electrical connections. Testing of the gasoline tanks about 50 feet away confirmed that the source of the subsurface hydrocarbons was a small leak in one of the storage tanks. A site investigation was initiated with five test borings around the leaking tank. On-site analysis of soil samples revealed the highest concentrations of hydrocarbons were located at or just above the GWT, which was between 8 and 11 feet below the ground surface. Hydrocarbons were generally nondetectable at depths of about 10 to 15 feet below the GWT. Based on five test borings around the leaky storage tank, the lateral extent of contamination in the unsaturated zone was estimated to be limited to a radius of less than 80 feet from the tank.

Soil/Site Conditions: Concrete pavement covered the site. Beneath that, clayey soils extended to a depth of 6 to 15 feet where subsoils graded to silt and gradually into a fine sandy saprolite below. Wells were installed in the test borings and were designed so they could be used for both vacuum extraction and the monitoring of water quality. One well near the tanks had about 10 inches of gasoline floating on the groundwater.

Experimental/System Design: The soil vapor extraction system consisted of an extraction well; a vacuum pump; various plumbing and valves; an air/water separator; and monitoring wells. The objective of the subsurface clean-up operation was rapid removal of free gasoline and residual hydrocarbons that were the source of subsurface vapors and groundwater contamination. After careful consideration of the entire subsurface problem, a vacuum recovery system was designed and mobilized to the site. The process proved effective for all four phases of subsurface hydrocarbon contamination problem by removing the free product, the residual hydrocarbons above the water table, subsurface vapors, and contaminated groundwater.

Status of Experiment/Site Clean-Up: The day after the vacuum system was installed, 22 inches of rain fell during the next three days causing the GWT to rise to within 1 foot of the surface. As a result of all the rainfall, the unsaturated zone was reduced to a depth of 1 foot and thus was located above the intake points of the extraction wells. The vacuum system was used to recover hydrocarbons from the utility conduit until the water table was lowered. Careful pumping from one extraction well, without lowering the GWT below the pre-storm depth of 8 to 11 feet below the ground surface, yielded about 4600 gallons of water. This dewatered the soil enough for the vacuum system to commence operation.

When operation started, there was 6 inches of gasoline in one well. At first the system was used for a three-phase recovery method. The simultaneous recovery of free gasoline, hydrocarbon vapor, and contaminated groundwater eliminated the free gasoline within 2 weeks. Hydrocarbon vapor concentrations dropped 80% as the vacuum operation continued.

The endpoint criteria for unsaturated clean-up dictated by the utility company was that hydrocarbons be nondetectable or less than 5% of the lower explosive limit in the utility conduit. A horizontal extraction system was installed near the utility line and connected to the vacuum extraction system in order to speed up the clean-up of the unsaturated zone.

After eight weeks of operation, the utility company tested the manhole and conduit line for hydrocarbon vapors. Even though the utility company's safety personnel could not detect hydrocarbon vapors in the manhole and conduit, there was concern that the vapors would return once the vacuum system was shut off. To ensure the complete removal of hydrocarbons, operation of the soil vapor extraction system was terminated for one week. Hydrocarbon vapors were still not detected in the manhole and conduit.

Overall, the vacuum operation removed 1600 pounds of hydrocarbons from the soils and the groundwater at the site. During this time, all traces of free gasoline were removed from the shallow GWT. The vapor problem was eliminated because the residual hydrocarbons and free gasoline had been effectively removed. In addition, hydrocarbon concentrations in the groundwater were reduced over 98%.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Groveland Wells
EPA Superfund Site

Principal Investigators:

Terra Vac Corporation
356 Fortaleza St.
Box 1591
San Juan, Puerto Rico 00903

Peter Michaels, Technology Evaluation Manager
Enviresponse Inc.
Building 209, Bay F
GSA Raritan Depot
Woodbridge Avenue
Edison, New Jersey 08837

Investigative Reports:

Enviresponse, Inc., "Demonstration Test Plan, In-Situ Vacuum Extraction Technology, Terra Vac Inc., SITE Program, Groveland Wells Superfund Site, Groveland, MA," EERU Contract No. 68-03-3255, Work Assignment 1-R18, Enviresponse No. 3-70-06340098, Edison, NJ, November 20, 1987

Alliance Technologies Corp., "Quality Assurance Project Plan, Terra Vac Inc., In-Situ Vacuum Extraction Technology, SITE Demonstration Project, Valley Manufactured Products Site, Groveland, MA," Contract No. 68-03-3255, Bedford, MA, September 1, 1987

Location Of Work/Study: Valley Manufactured Products Co., Inc., Groveland, MA, which is located on the north side of Washington Street and is approximately 400 feet west of Mill Pond. The building is 285′ long by 105′ wide.

Nature of Contamination: Valley Manufactured Products Co., Inc. has been in operation since 1964 and has used different types of cutting oils and degreasing solvents including trichloroethylene (TCE), tetrachloroethylene (PCE), trans-1,2-dichloroethylene (DCE), methylene chloride, and 1,1,1-trichloroethane. The sources of contamination were a leaking underground storage tank and the previous improper storage and handling practices of these solvents and oils. The highest concentration is located beneath the building. The highest concentrations at the location of the oil storage area were 2500 mg/kg of TCE, 40 mg/kg of PCE and 12 mg/kg of 1,2-DCE at 4 to 12 feet deep. These depths generally lie above a clay lens. Total VOC contamination levels ranged from nondetectable to 9 mg/kg to 20.4 mg/kg within the clay lens. A dense sand layer located below this clay lens and above the groundwater table had VOC contamination levels up to 20.4 ug/g. The contamination plume is moving in a north-easterly direction towards Mill

Pond. Two of Groveland's municipal wells have already been contaminated.

Soil/Site Conditions: The ground surface slopes downward northeasterly towards the Mill Pond, with Johnson Creek and Mill Pond acting as discharge zones for groundwater flow from the Valley site. The clay lens is approximately 5 to 12 feet below the surface and has an average thickness of 5 to 10 feet. It extends under the area where the highest levels of VOC contamination were detected. During periods of increased rainfall, the contamination under the building is transported vertically through the clay lens and percolates downward into subsequent subsoil strata due to rising and falling groundwater tables. The GWT varies from 27' to 52' below the land surface. Once this contamination reaches the groundwater table, it moves along with the average groundwater flow field from the Valley site northeasterly toward Mill Pond.

Experimental/System Design: The demonstration soil vapor extraction system consisted of extraction wells; an air/water separator; a vacuum pump; various plumbing, valves, gauges, and sampling ports; and monitoring wells. Vapor treatment at this site consisted of GAC adsorption. Figure 1 shows the overall system layout along with the building location and approximate location of the VOC plume. A conventional industrial blower was used to create the vacuum applied to the extraction wells located in the contamination zone. The perforated extraction wells were 24 feet in depth and were connected by piping to an air/water separator. The exhaust gases were treated by an activated carbon adsorption system. This absorption system, located upstream of the blower intake, consists of manifolded activated carbon canisters. Backup canisters were provided as insurance against possible contaminant breakthrough into the exhaust. Subsurface vacuum and vapor concentrations were monitored by strategically located monitoring wells which also served to provide supply air to the contamination zone. These monitoring/injection wells were located around the extraction wells as shown in Figure 1.

Status of Experiment/Site Clean-up: The demonstration system was in an active treatment stage with part of the contamination being cleaned up under the EPA Superfund SITE Program. The demonstration project was temporarily suspended due to operational problems. The system was restarted, and the SITE demonstration continued into April 1988. The major operational problems were that too much water was being extracted from soil and that carbon usage was excessive. The carbon canisters should have been placed on exhaust side of blower to heat air to reduce relative humidity and increase carbon capacity.

A site visit was made by Dr. N.J Hutzler of Michigan Tech on 1/15/88.

Reproduced from best available copy.

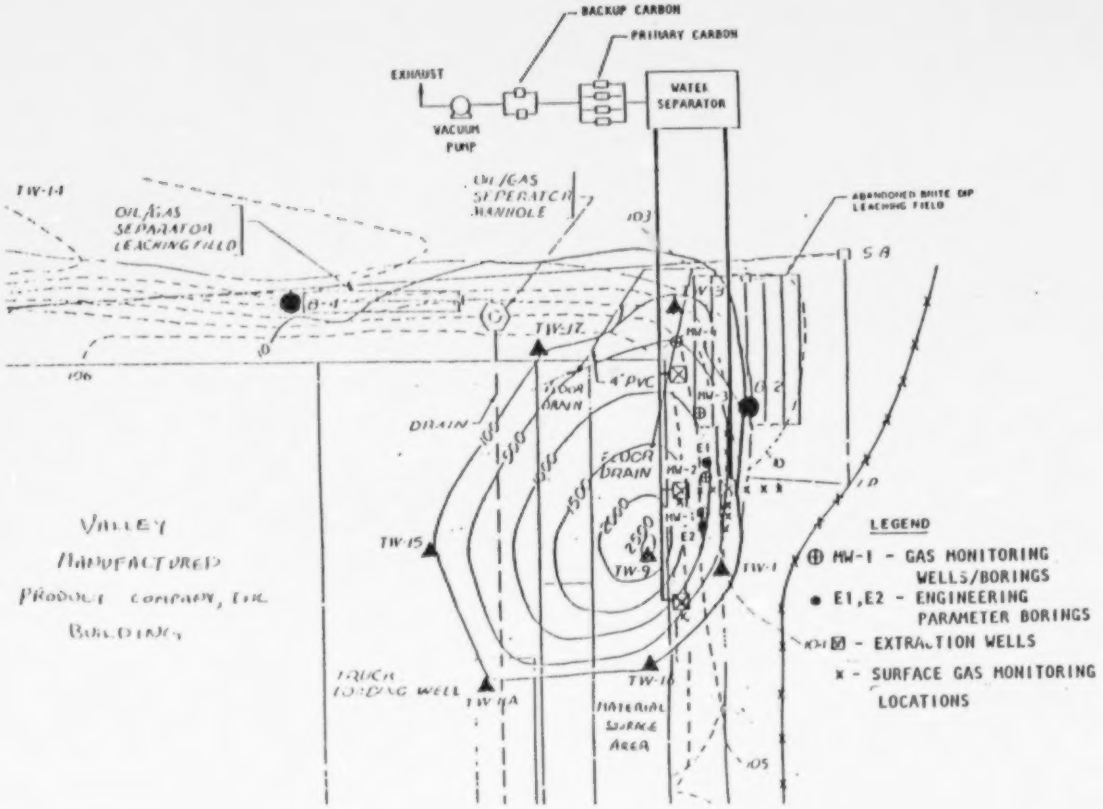

BACKUP CARBON
PRIMARY CARBON
EXHAUST
VACUUM PUMP
WATER SEPARATOR
TW-14
OIL/GAS SEPARATOR LEACHING FIELD
OIL/GAS SEPERATOR MANHOLE
103
ABANDONED WHITE DIP LEACHING FIELD
SA
TW-17
106
4" PVC
FLOOR DRAIN
DRAIN
MW-4
MW-3
E1
E2
MW-2
MW-1
TW-9
TW-15
TW-1
TW-16
TW-4A
TRUCK LOADING WELL
MATERIAL STORAGE AREA
105
104
VALLEY MANUFACTURED PRODUCT COMPANY, INC. BUILDING
LEGEND
MW-1 - GAS MONITORING WELLS/BORINGS
E1,E2 - ENGINEERING PARAMETER BORINGS
EXTRACTION WELLS
SURFACE GAS MONITORING LOCATIONS

Figure 1. Site Plan and Soil Vapor Extraction System Design for Groveland, MA (Source: Enviresponse, 1987).

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Hill Air Force Base, Refueling Area, Bldg. 914

Principal Investigators:

David DePaoli and Steve Herbes
Oak Ridge National Laboratory
Martin Marietta Energy Systems, Inc.
Oak Ridge, TN 37831

Lt. Michael Elliot/Capt. Ed Heyse
RDVW
U.S. Air Force Engineering and Services Center
Tyndall AFB, FL 32403

Rollins, Brown and Gunnell. Inc.
1435 West 820 North
P.O. Box 711
Provo, Utah

Investigative Reports:

Oak Ridge National Laboratory, "Draft: Preliminary Test Plan, In-Situ Soil Venting Demonstration, Hill AFB, Utah," conducted by Oak Ridge National Laboratory, for the Air Force Engineering and Services Center, Tyndall AFB, FL, 1987.

Radian Corp., "Installation Restoration Program Phase II Draft Report," prepared for Hill AFB, UT, July 1987.

Rollins, Brown, and Gunnell, Inc., "Subsurface Investigation and Remedial Action, Hill AFB JP-4 Fuel Spill," Provo, Utah, December 1985.

Location of Work/Study: The contamination area is about 100 yards west of the north end of Building 914 on Hill Air Force Base, Utah. Building 914 is about one mile north and 3/4 of a mile west of the South Gate, which is the Visitor's Entrance. Hill AFB is about 20 miles north of Salt Lake City, Utah, and about 8 miles south of Ogden, Utah, just a few miles east of I-15.

Nature of Contamination: The area is contaminated with over 25,000 gallons of JP-4 (jet fuel). The spill occurred on January 9, 1985. Most of the fuel infiltrated below the overflowing fuel storage tanks, and the remainder flowed to the west across an area of approximately 90 feet by 140 feet.

Soil/Site Conditions: The contaminated area is relatively flat and isolated from traffic, residential buildings, and surface water. The area directly below the tanks is now covered by a concrete pad placed at an elevation of approximately 15 feet below grade. The soil from the surface to a depth of approximately 50 feet is a fine sand mixed with gravel. It is relatively dry. Compact clay layers lies below the sand and can be found to depths of approximately 600 feet. A groundwater aquifer is below the clay.

Experimental/System Design: This project is still in the preliminary stages. The soil vapor extraction system is being installed. The site, when completed, will consist of three extraction configurations operating in parallel as depicted in Figures 1 and 2. Each extraction system will consist of extraction wells; a gas flow meter; various plumbing, valves, gauges, and sampling ports; along with monitoring wells and sensors. A common blower and catalytic incinerators for vapor treatment will serve all three systems. The soil excavated from below the tanks was piled on-site on a plastic membrane liner. The pile is approximately 10 feet high, 52 feet wide, and 100 feet long (52,000 cubic yards). Eight pipes are buried horizontally, equally spaced and perpendicular to the long axis of the pile. The pile is to be covered to prevent blowing dirt.

Prior to the installation of the concrete pad on the area below the tanks, soil samples were taken to a depth of 25 feet below the excavation. Vapor and pressure sensors were installed in the augered holes. In addition, 6 trenches were dug to 5 feet below the excavation, and vent pipes were installed.

The area west of the tank area, where the fuel seeped into the soil, is to be vented with a grid work of vertical extraction wells. This system was designed after a preliminary one-well venting test was performed. The one-well test equipment consisted of a single extraction well surrounded by vapor and pressure sensors at various distances from the extraction well and at various depths and was designed to determine the radius of influence of the extraction well and the air permeability of the soil. Fourteen additional extraction wells and 25 additional pressure monitoring points are being installed. The extraction wells are designed such that they can be operated as passive air inlets.

The blower/emission control system is common to the three venting subsystems, will provide vacuum for inducing air flow, and will treat emissions as necessary to meet regulatory requirements. The catalytic incinerator unit can be operated at air flows up to 1000 cfm until the extraction gas reaches a hydrocarbon concentration of 0.0002 g/L, at which time the gas can be discharged directly. This unit will destroy over 99% of the hydrocarbons in the extracted gas and will be capable of handling fumes ranging from 0.25 g/L to 0.0002 g/L. Granular activated carbon may be used for vapor treatment at lower hydrocarbon concentrations.

Status of Experiment/Site Clean-up: As of summer 1988, this site is in the pretreatment stage. Horizontal wells in the pile and under the tank pad are in place but not operating. Vapor and pressure sensors are in place under the pad. The pad is in place, and the tanks have been replaced. The pile has been exposed to the atmosphere for several months. One vertical extraction well is in place for the radius of influence and hydrocarbon concentration study. Several vapor and pressure sensors are in place around the extraction well in a semi-circle at different distances and depths. No free product has been found and is thought to be immobilized in the soil.

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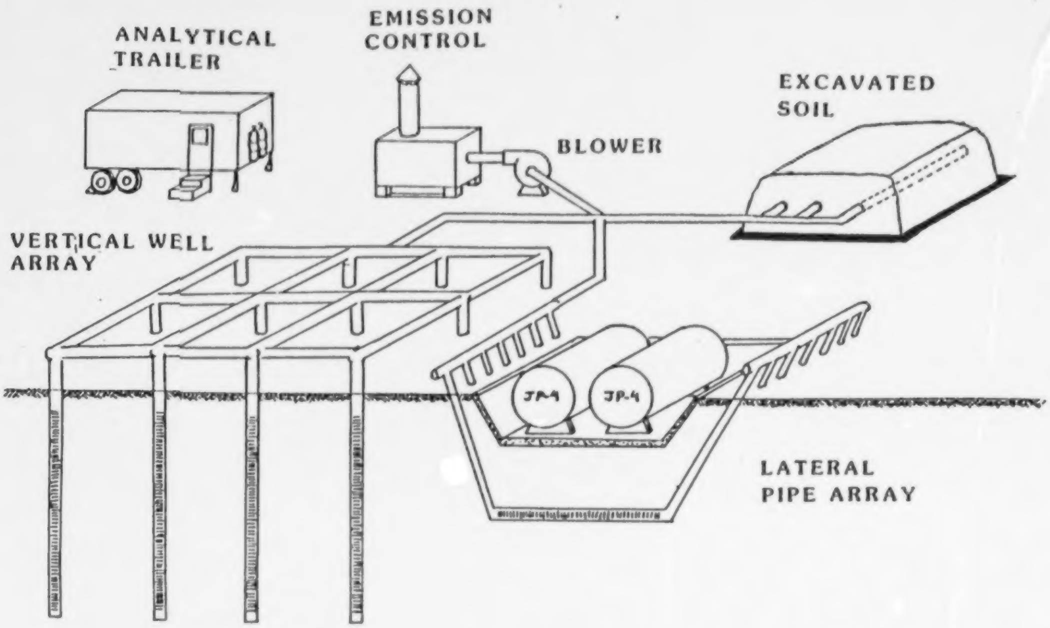
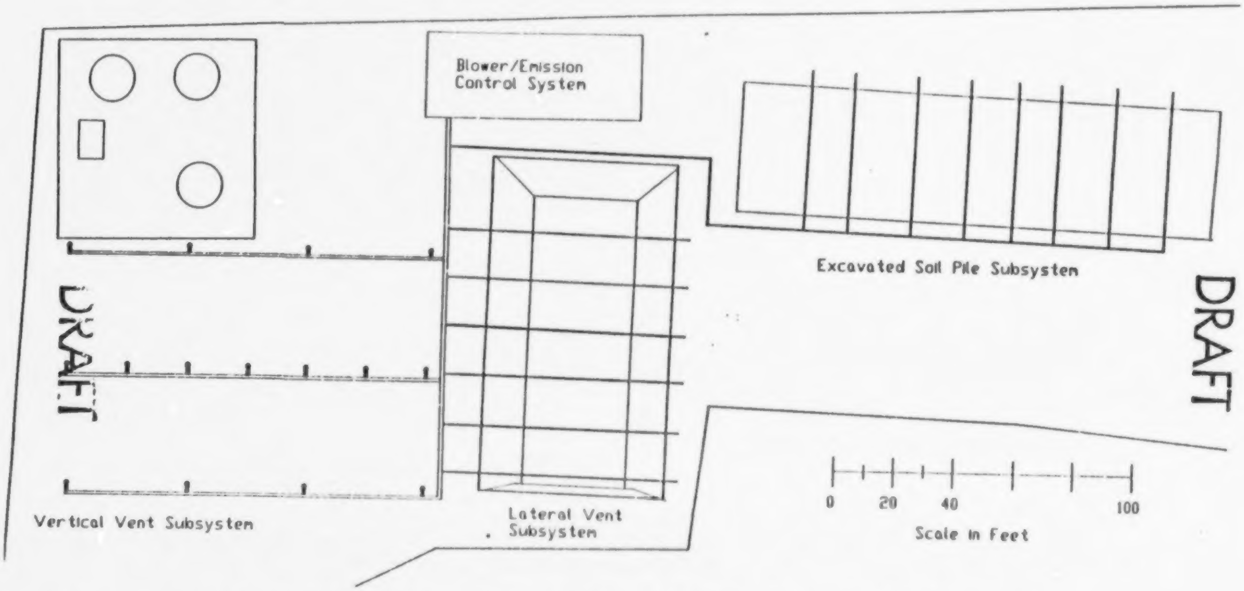

ANALYTICAL TRAILER
EMISSION CONTROL
EXCAVATED SOIL
BLOWER
VERTICAL WELL ARRAY
JP-4
JP-4
LATERAL PIPE ARRAY

Figure 1. Conceptual Diagram of Soil Vapor Extraction Demonstration Project at Hill Air Force Base (Source: Oak Ridge National Lab, 1988).


Blower/Emission Control System
Excavated Soil Pile Subsystem
Vertical Vent Subsystem
Lateral Vent Subsystem
0
20
40
100
Scale in Feet

DRAFT

DRAFT

Figure 2. Soil Vapor Extraction System Layout at Hill Air Force Base (Source: Oak Ridge National Laboratory, 1988)

Chronological Sequence of Events:

01/09/85 -- Spillage of ~26,000 gallons of JP-4, 1000 gallons recovered.

12/85 -- Remedial Investigation by Rollins, Brown and Gunnell. Concluded no imminent danger.

07/87 -- Radian Corporation investigated site further. Recommended additional monitoring.

07/22/87 -- D. DePaoli and S. Herbes of ORNL and Capt. E. Heyse of AFESC, Tyndall AFB visited and selected Hill AFB as study site.

08/18/87 -- DePaoli proposed design for horizontal extraction wells in pile and under tank pad for installation during tank excavation and pad construction.

08/31/87 -- DePaoli and Herbes propose soil sampling scheme.

10/87 -- Tanks were excavated, horizontal pipes installed, and soil borings performed.

01/10-22/88 -- D. DePaoli, H. Jennings, J. Wilson, D. Gillespie, and Capt. E. Heyse conducted one-well vent test.

01/14-17/88 -- J. Gierke (MTU) visited site and aided in one-well test preparation.

04/21/88 -- Test plan developed by ORNL reviewed by N.J. Hutzler and others and tentatively approved by U.S.A.F. Tentative starting date is late summer 1988.

06/17/88 -- Specifications of vent wells, pressure monitoring wells, and plastic cover prepared by ORNL.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Industrial Tank Farm in San Juan, Puerto Rico

Principal Investigators:

James J. Malot
Terra Vac Corporation
356 Fortaleza St.
Box 1591
San Juan, Puerto Rico 00903

Paul R. Wood
Applied Technologies Group
2200 N.E. 124th. Street
North Miami, FL 33181

Investigative Reports:

Malot, J.J., "Unsaturated Zone Monitoring and Recovery of Underground Contamination," Terra Vac, Inc., P.O. Box 550, Dorado, Puerto Rico 00646, Presented at the Fifth National Symposium on Aquifer Restoration and Ground Water Monitoring, May 21-24, 1985.

Malot, J.J., Jose C. Agrelot, and Melvin J. Visser, "Vacuum: Defense System For Ground Water VOC Contamination," Presented at the Fifth National Symposium on Aquifer Restoration and Ground Water Monitoring, Columbus, Ohio, May 21-24, 1985.

Malot, J.J., and P.R. Wood, "Low Cost, Site Specific, Total Approach to Decontamination," presented at the Conference on Environmental and Public Health Effects of Soils Contaminated with Petroleum Products, University of Massachusetts, Amherst, MA, October 30-31, 1985.

Location of Work/Study: Approximately 60 km. west of San Juan, Puerto Rico, on the north side of the island

Nature of Contamination: In mid August 1982, approximately 15,000 gallons (200,000 pounds) of carbon tetrachloride leaked from an underground storage tank. Subsurface investigation revealed extensive contamination in the unsaturated zone and widespread contamination of the aquifer. Roughly 4,400,000 cubic yards of soil and bedrock were estimated to be contaminated within the unsaturated zone. Groundwater VOC concentrations reached 3000 ppbv in a water supply well 3000 feet away.

Soil/Site Conditions: Between 40 and 210 feet of layers of clayey silts and silty clays with fine grained sands interspersed are present beneath the tank. About 900 feet of the Aymamon and Aquada Limestone Formations underlie the fine grained soils. These limestone formations are 90 to 98% calcium carbonate, very permeable, and riddled with solution channels. They contain bedding planes that dip in the direction of groundwater flow (north-northeast) at a 4-degree angle. Below these limestone layers are the Ciabo and Lares Formations which contain an artesian aquifer. The top of the unconfined aquifer is about 300 feet below the ground surface.

Experimental/System Design: Two systems (Vacuum System I and Vacuum System II) were installed. Each system consisted of one extraction well; a vacuum pump; various plumbing and valves; a condenser; and monitoring wells. While groundwater recovery operations were beginning, a pilot vacuum extraction system was designed and installed. A vacuum pump, cold water condenser, and recovery tank made up the above-ground vacuum system. The extraction well's intake was located and sealed in the unsaturated zone between depths of 25 and 75 feet. A concrete cover was constructed over the tank farm to reduce the possibility of contaminant migration into the aquifer due to infiltration from rainfall.

Status of Experiment/Site-Cleanup: Vacuum System I was installed in contaminated clayey soils to depths ranging from 75 to 180 feet. The initial vacuum reading in the clayey soil was 29.9 inches of mercury. Approximately 3 weeks after this vacuum was applied to the wells, the radius of influence had moved out three feet and the vacuum was now 26 inches of mercury at the well head. As a result of subsurface vacuum and vapor flow rate monitoring of the extraction well, it was determined that the development of an effective radius of influence of more than a few feet took several weeks. This subsurface vacuum stabilized about 90 days later with an influence radius greater than 10 feet. The flow rate of recovered contaminants increased as the subterranean pressure gradient continued to propagate. After the first 3 weeks, carbon tetrachloride was being extracted at a rate of 250 pounds per day.

A similar system, Vacuum II, was developed for vacuum extraction from the fractured bedrock in the unsaturated zone up to 300 feet deep. Vacuum System II used air dispersion exhaust stacks to treat the recovered contaminants. The operation of the two vacuum systems together proved to be the most cost effective source control alternative at the site.

During the development of the vacuum extraction system, contaminated groundwater was recovered from the deep aquifer. Initially a downgradient water supply well was sacrificed to control the migration of the contaminate in the aquifer. Later a second well was installed to cleanup the existing contamination in the aquifer.

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Custom Products, Inc.
Stevensville, Michigan

Principal Investigator: Dr. Frederick C. Payne
Midwest Water Resources, Inc.
Charlotte, Michigan

Investigative Reports:

Payne, F.C., C.P. Cubbage, G.L. Kilmer, and L.H. Fish, "In Situ Removal of Purgeable Organic Compounds from Vadose Zone Soils," presented at the Purdue Industrial Waste Conference, May 14, 1986.

Payne, F.C., and J.B. Lisiecki, "Enhanced Volatilization for Removal of Hazardous Waste form Soil," Proceedings of the 5th National Conference on Hazardous Wastes and Hazardous Materials, HMCRI, Las Vegas, NV, April 19-21, 1988.

Location of Work/Study: Custom Products, Inc., Stevensville, Michigan.

Nature of Contamination: During mid-1984, a VOC plume was discovered in a useable aquifer. Perchloroethylene (PCE) was found to be the principal contaminant reaching levels in excess of 100 ug/L in domestic water wells and levels of 800 ug/L in nearby industrial production wells. PCE levels on the unsaturated soil ranged from 8.3 to 5,600 mg/kg dry weight. A PCE tank sludge discharge location outside an exterior wall had a soil surface contaminant loading of 110 mg/kg. The estimated volume of contaminated soil ranged from 1000 to 2000 cubic yards.

Soil/Site Conditions: The unsaturated zone extended to 30-feet below the surface and consisted of fine sand throughout.

Experimental/System Design: The soil vapor extraction system consisted of six injection wells and one extraction well; a 6 mil-polyethylene impermeable cap; a rotary vane vacuum pump; a gas flow meter; various plumbing, valves, gauges and sampling ports; and GAC vapor treatment. The system forced clean air into the unsaturated zone at a radius outside the contaminated region and pulled the clean air toward the center of the contaminated area where it was withdrawn under reduced pressure. See Figure 1. The removal system's central vacuum extraction well was installed in a 5-inch borehole, 25 feet deep, at the location where the PCE sludge had been applied to the soil surface. It was gravel-packed from the 17 to 25-foot depths, and a 2-inch galvanized casing was installed from one foot above grade to the 17-foot depth. The casing was then gravel-packed from the 8 to

17-foot depth and cemented from the ground surface to the 8-foot depth.

Five air injection wells were constructed at a 50-foot radius from the central extraction well on the contaminated side of the building. A sixth injection well was located at the opposite side of the building at a distance of 70 feet. Each injection well consisted of a 5-inch diameter, 25-foot deep borehole which was gravel-packed from 19 to 25 feet. One and one quarter-inch PVC casing was installed from 1 foot above grade to the 19-foot depth and was then gravel-packed to the 15-foot depth. The injection wells were cemented from the ground surface down to the 15-foot depth to allow clean air to be blown into the deeper strata.

The surface of the entire site was sealed with 6-mil polyethylene sheeting. The cap was covered with sand to secure it to the ground surface and protect it against puncture. The polyethylene cover provided better control over the pathway that the air took, resulting in radial movement of air toward the extraction well rather than vertically from the soil surface.

The blower/activated carbon system was constructed inside a building on-site. Air flowed from the extraction well through a 2-inch galvanized pipe to a filtration bed filled with 1200 pounds of granular BPL activated carbon. The extracted air entered the bottom of the filter bed through a liquid trap and exited through the tank top. Exhaust air from the filter bed moved through a 2-inch galvanized pipe to a 1-horsepower oilless rotary vane vacuum pump. The discharge air from the vacuum pump was distributed to the injection wells through a manifold with individual valves for each line that allowed balancing of injection pressures. Overall system cost was about $60,000.

Status of Experiment/Site Clean-Up: Operation of this system began on December 11, 1985. The vacuum at the central extraction well was 4.5 inches of mercury, and the air flow rate was 10.4 cfm. During the first 48 hours of pumping, PCE recovery was extremely high. Approximately 1.7 pounds of PCE was removed in liquid form. By 48 hours, levels of the recovered gaseous PCE reached 92,000 mg/m^3 and then declined to 6,000 mg/m^3 by 72 hours. During these three days of operation of this system, a peak PCE concentration of 180,000 mg/m^3 air was reached and then declined to 5,000 mg/m^3 air. Through day 12, gaseous PCE levels remained near 5,000 mg/m^3 in the central extraction well. On the 19th day, the collected PCE sample was 1,000 mg/m^3 and by day 35 declined to 10 mg/m^3. Figure 2 shows the accumulated PCE levels recovered at the end of the 35 days. At the end of 45 days PCE levels declined to 10 mg/m^3 air and the contaminant level in soil was less than 1 mg/kg soil. According to the authors, the operational cost of this system was less than 20 percent of the projected excavation cost.

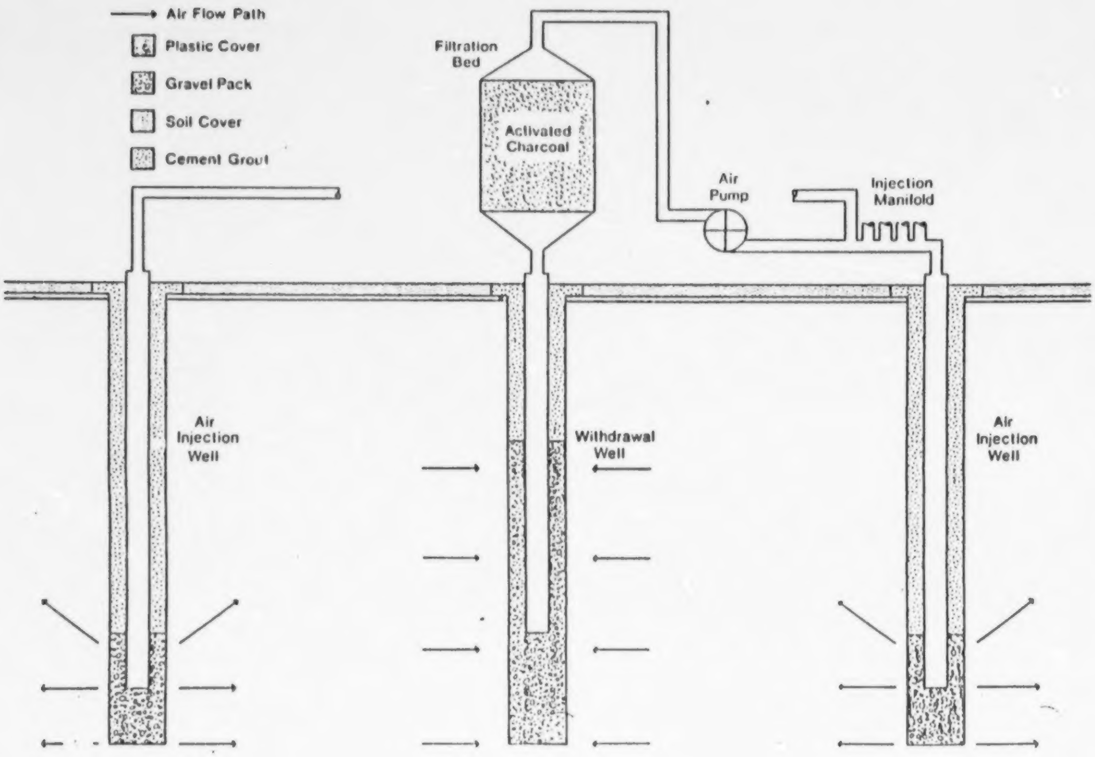

Air Flow Path
Plastic Cover
Gravel Pack
Soil Cover
Cement Grout
Filtration Bed
Activated Charcoal
Air Pump
Injection Manifold
Air Injection Well
Withdrawal Well
Air Injection Well

Figure 1. Closed Loop Soil Vapor Extraction System at Stevensville, MI (Source: Payne et al., 1986)

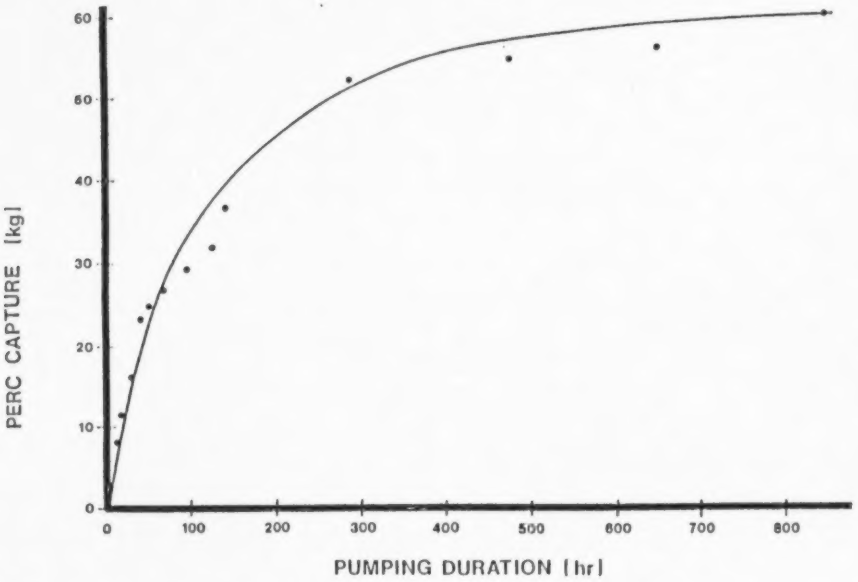


Figure 2. Perchloroethylene Removal at Stevensville Site (Source: Payne et al., 1986).

ASSESSMENT OF PILOT-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: South Tacoma Channel Well 12A
Time Oil Company

Principal Investigators: Woodward-Clyde Consultants
One Walnut Creek Center
100 Pringle Avenue
Walnut Creek, CA

Investigative Report:

Woodward-Clyde Consultants, "Performance Evaluation Pilot Scale Installation and Operation Soil Gas Vapor Extraction System Time Oil Company Site Tacoma, Washington, South Tacoma Channel, Well 12A Project," Work Assignment No. 74-0N14.1, Walnut Creek, California, December 1985.

Location of Work/Study: Time Oil Company
Tacoma, Washington

Nature of Contamination: A remedial investigation by the consulting firm of CH_2M-Hill determined that soils in the vicinity of Time Oil Company property were contaminated with a large number of VOCs, primarily straight-chain, polychlorinated, volatile organic solvents such as tetrachloroethane and trichloroethylene, as listed in Table 1. Contamination levels in the soil ranged from concentrations up to 5000 ppb at depths to 30 feet, which was the approximate surface of the GWT at the time of sampling, to values greater than one million ppb at 6 inches below the ground surface. The contaminant appeared to cover an approximate area of 30,000 square feet, including the area covered by a foundation slab that served to support several storage tanks. The groundwater beneath the site contained significant levels of VOCs, most likely due to leaching by infiltrating precipitation percolating through the contaminated soil. It was expected that, without correction, VOCs in the soil would continue to leach into the groundwater.

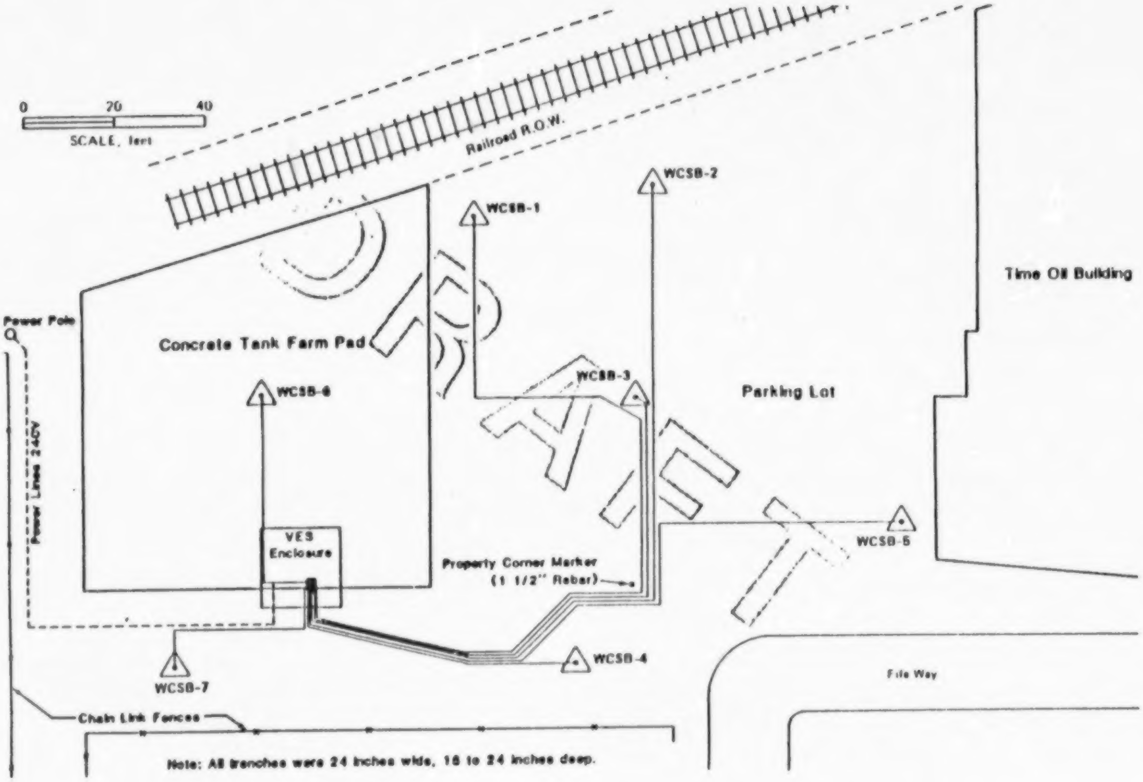
Soil/Site Conditions: The soil at this site is described as sandy and gravely with some silt and is generally relatively permeable with a hydraulic conductivity of approximately 3.0×10^{-3} centimeters/second.

Experimental/System Design: The system as installed consisted of seven extraction wells; a vacuum pump; a gas flow meter; and various plumbing, valves, gauges, and sampling ports. The system was designed to allow all of the wells to operate as either extraction or air-inlet wells. Figure 1 shows the overall well layout, and Figures 2 and 3 diagram the system design. The soil-gas extraction wells were constructed of 2 inch PVC casing and screened from approximately 5 feet above the GWT to 6 feet below the ground surface. Due to the high permeability of the soils at this site, short-circuiting of air through the upper six feet appears to have been a significant problem. The installation of the VES was completed on 7 August 1985. A temporary discharge waiver was granted for operation while data on the actual discharges from this site were being collected during the month of August. On 8 August 1985, the system was operated about eight hours per day for three days to check flows and pressures within the system. Continuous operation began on 13 August 1985. Data collection began on 14 August 1985 and continued for 10 days. During this period, the system was operated under balanced flow conditions, with approximately 30 cfm drawn from each well. Eighty-four vapor samples were collected during this 10 day period. Samples were analyzed by gas chromatography and mass spectrometry (GC/MS) to permit detection of the widest possible range of chemicals. At the on-site mobile Laboratory, a Varian Model 330 Gas Chromatograph was fitted with an electron capture detector (GC/ECD) for optimum quantification of the major known soil contaminants: 1,1,2,2-tetrachloroethane, 1,1,2-trichloroethane, trichloroethylene, and 1,2-dichloroethylene.

An average total volatiles extraction rate of approximately 22 pounds per day and a peak extraction rate of 25 pounds per day were achieved at this site. The pilot-scale system was designed to utilize seven soil borings which had been located at the site for the purpose of determining soil and contamination characteristics. Since the soil-gas extraction wells could not be located in areas of highest contamination until the initial site characterization data were available and the project was limited by the time available, the wells for the pilot-scale VES project were simply installed in the existing soil bore holes as an expedient and cost-saving measure. To optimize this system's operation, the extraction wells should be located in those areas within the site that have the highest contamination while, the air-inlet wells should be located in the adjacent areas of lowest concentration to maximize the air-sweeping effect of the system.

To enhance system performance, Woodward-Clyde suggests that the wells should have been constructed with approximately 20 feet of casing between the top of the screen and the soil surface or that the soil surface should be capped with plastic or asphalt. In addition, the wells should be screened to the water table surface to assist in the extraction of deep contamination.

Status of Experiment/Site Clean-up: It was determined that extraction rates in excess of 25 pounds per day of VOCs could be achieved with the existing pilot system. Based on these results, Woodward-Clyde engineers recommended that the existing system be expanded and modified and that it be operated continuously until the concentration of volatiles in the extracted soil-gas decreased to levels acceptable with local health officials. The suggested modifications included the addition of more extraction wells, air inlets, and vapor treatment. Six new extraction wells with perforations from 20 feet below the ground surface to the water table at its lowest seasonal elevation -- approximately 35 feet below the ground surface -- were recommended. Four new air inlet wells with perforations extending from approximately 10 feet to 35 feet below the ground surface were proposed for the system. It was recommended that most of the existing wells should be operated as air inlet wells, since they were perforated to approximately 5 feet below the ground surface. A vapor phase carbon bed adsorption system should be added to control emissions to the air. The existing blower assembly was considered satisfactory for continued operation of the system. It was further recommended that the existing system be restored to operation as soon as possible in order to minimize the potential for additional VOCs being transported to the groundwater. The current status of the project is unknown.


0
20
40
SCALE, feet
Railroad R.O.W.
WCSB-2
WCSB-1
Time Oil Building
Power Pole
Concrete Tank Farm Pad
WCSB-3
Parking Lot
WCSB-6
Power Lines 240V
VES Enclosure
WCSB-5
Property Corner Marker
(1 1/2" Rebar)
WCSB-4
WCSB-7
File Way
Chain Link Fences

Note: All trenches were 24 inches wide, 18 to 24 inches deep.

Figure 1. Time Oil Company Site Plan with Well and Piping Locations (Source: Woodward-Clyde, 1985).

Reproduced from best available copy.

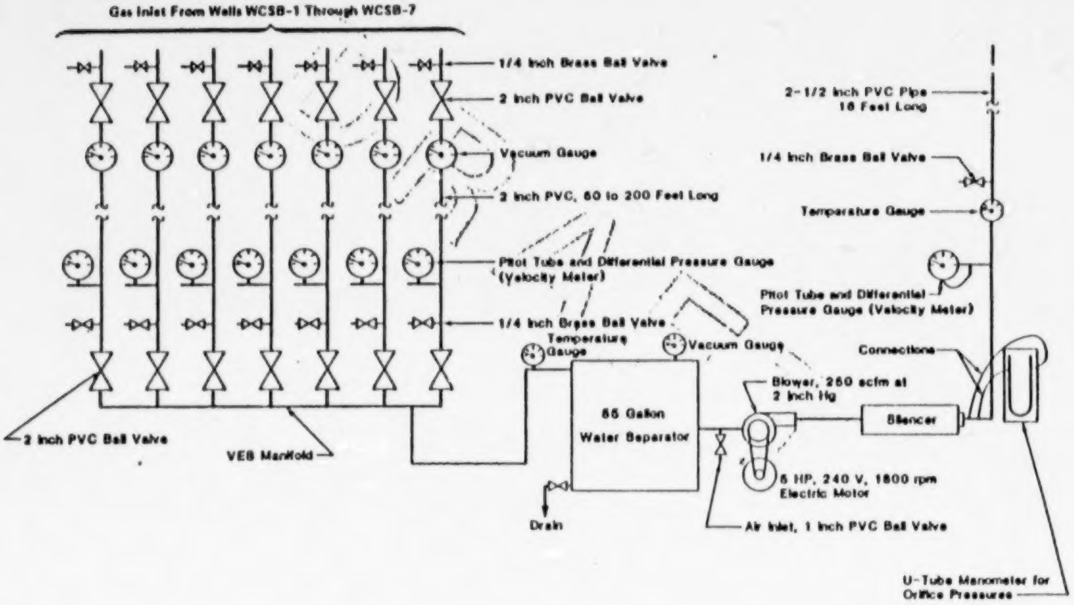
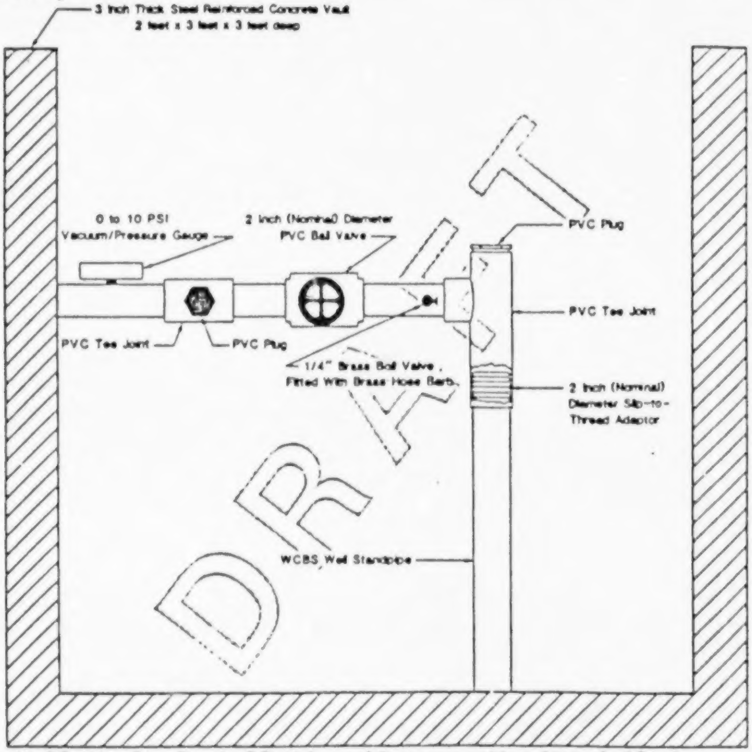

Gas Inlet From Wells WCSB-1 Through WCSB-7
1/4 Inch Brass Ball Valve
2 Inch PVC Ball Valve
Vacuum Gauge
2 Inch PVC, 60 to 200 Feet Long
Pitot Tube and Differential Pressure Gauge (Velocity Meter)
1/4 Inch Brass Ball Valve
Temperature Gauge
Vacuum Gauge
2 Inch PVC Ball Valve
VES Manifold
55 Gallon Water Separator
Drain
Blower, 250 scfm at 2 Inch Hg
Silencer
5 HP, 240 V, 1800 rpm Electric Motor
Air Inlet, 1 Inch PVC Ball Valve
2-1/2 Inch PVC Pipe 18 Feet Long
1/4 Inch Brass Ball Valve
Temperature Gauge
Pitot Tube and Differential Pressure Gauge (Velocity Meter)
Connections
U-Tube Manometer for Orifice Pressures

Figure 2. Time Oil Company Vapor Extraction System Design (Source: Woodward-Clyde, 1985).


3 Inch Thick Steel Reinforced Concrete Vault 2 feet x 3 feet x 3 feet deep
0 to 10 PSI Vacuum/Pressure Gauge
2 Inch (Nominal) Diameter PVC Ball Valve
PVC Plug
PVC Tee Joint
PVC Plug
PVC Tee Joint
1/4" Brass Ball Valve, Fitted With Brass Hose Barb
2 Inch (Nominal) Diameter Slip-to-Thread Adaptor
WCBS Well Standpipe

DRAFT

Figure 3. Time Oil Company Well Vault Installation (Source: Woodward-Clyde, 1985).

TABLE 1

CONTAMINANTS IDENTIFIED IN SOILS FROM THE TIME OIL COMPANY PROPERTY

COMPOUND	MAXIMUM MEASURED CONCENTRATIONS micrograms/kilogram (ppb)
Volatiles	
1,1,2,2-tetrachloroethane	210,000
(1,1,2,2-tetrachloroethane + tetrachloroethylene)	1,030,000
trichloroethylene	106,000
trans-1,1-dichloroethylene	3,920
methylene chloride	26,100
vinyl chloride	28
toluene	720
acetone	900
1,1,1-trichloroethane	3,080
chlorobenzene	1,430
2-butanone	780
1,1-dichloroethylene	3
(1,1,2-trichloroethane + cis-1,3-dichloropropene + chlorodibromomethane)	3,210
(1,1,1-trichloroethane + 2-chloroethylvinyl ether)	108
carbon tetrachloride	5
carbon disulfide	27
methylbromide	5
Base Neutrals and Acids	
(1,2-dichlorobenzene + 1,4-dichlorobenzene)	2,200
2-methyl naphthalene	12,000
naphthalene	7,200

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Twin Cities Army Ammunition Plant (TCAAP)

Principal Investigators:
G.J.Anastos
Roy F. Weston, Inc.
West Chester, PA

Federal Cartridge
U.S. Army

Investigative Reports:

Anastos, G.J., P.J. Marks, M.H. Corbin, and M.F. Coia, Task 11. In Situ Air Stripping of Soils, Pilot Study, Final Report, Report No. AMXTH-TE-TR-85026, U.S. Army Toxic & Hazardous Material Agency, Aberdeen Proving Ground, Edgewood, MD, 88 pp., October 1985.

Oster, C.C., and N.C. Wenck, "Vacuum Extraction of Volatile Organics from Soils," Proceedings of the 1988 Joint CSCE-ASCE National Conference on Environmental Engineering, Vancouver, B.C., Canada, pp. 809-817, July 13-15, 1988.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System, Site G, First Week Operations Report", Twin Cities Army Ammunition Plant, New Brighton, MN, March 1986.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System Site D, Operations Report," Twin Cities Army Ammunition Plant, New Brighton, MN, September 8, 1986.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System Site D Operations Report," Twin Cities Army Ammunition Plant, New Brighton, MN, September 1, 1987.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System Site D, Operations Report," Twin Cities Army Ammunition Plant, New Brighton, MN, October 2, 1987.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System Site G, Emissions Control System Operations Report," Twin Cities Army Ammunition Plant, New Brighton, MN, September 1, 1987.

U.S. Army, "Twin Cities Army Ammunition Plant In-Situ Volatilization System Site G, Emissions Control System Operations Report," Twin Cities Army Ammunition Plant, New Brighton, MN, October 2, 1987.

Wenck Associates, Inc., "Project Documentation: Work Plan, ISV/In-Situ Volatilization, Sites D and G, Twin Cities Army Ammunition Plant," for Federal Cartridge Corporation, New Brighton, MN, prepared by: Wenck Associates, Inc., (WAI), Twelve Oaks Center, 15500 Wayzata Blvd., Wayzata, MN, September 1985.

Weston, Roy F., Inc., Installation Restoration General Environmental Technology Development Contract DAAK11-82-C-0017, Appendices -- "Task 11, In-Situ Solvent Stripping From Soils Pilot Study," prepared for U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, MD, prepared by Roy F. Weston, Inc., West Chester, PA, May 1985.

Location of Work/Study: Twin Cities Army Ammunition Plant
New Brighton, MN

Nature of Contamination: The two prominent sites of interest are sites D and G. Site D is located on the Arsenal Sand kame deposit and is believed to have been used for open burning prior to 1970. The extent of the stained sediments (gray-black), presumed to indicate burning or disposal, was mapped by Weston (4 June 1984 and May 1985). Soil samples indicate volatile organics, with TCE the most prominent, at concentrations up to 8,000 ppm. This was mainly in the upper 10 feet of the soil. However, soil borings as deep as 120 and 140 feet revealed TCE levels at 1,000 and 400 ppm, respectively. In addition, excessive levels of barium, chromium, lead, phenolics, and PCB's have also been found in the soils at site D.

Site G is located on the boundary between the Arsenal Sand kame deposit and the Twin Cities Formation. From the 1940's into the 1970's, site G was used as an open dump. Magnetic abnormalities in two regions of the site indicate buried drums or other metallic waste. Volatile organic concentrations up to 1,000 ppm were observed in soil samples taken along the eastern and southeastern boundary of the fill area in the upper 20 feet of the site. The predominant compounds were TCE and its degradation product, 1, 2-dichloroethylene. Excessive levels of cadmium, chromium, lead, and phenolics were discovered in site G soil samples.

Soil/Site Conditions: Both sites have homogeneous sandy soils, Arsenal Sand, as deep as 120 feet below the ground surface, well above the groundwater table. The groundwater table is located at a depth of 165 feet. This Arsenal Sand is in a kame deposit (a poorly-sorted, glaciofluvial, sand and gravel formation) that consists of brown-gray, fine to coarse sand and gravel. The Arsenal Sand has a 45 foot thick layer of Hillside Sand underneath it.

Experimental/System Design: Pilot- and full-scale studies have been conducted at TCAAP. The pilot study was conducted at Site D. The soil vapor extraction system for the pilot study consisted of injection and extraction wells; 2 blowers; a gas flow meter; various plumbing; insulation for the plumbing; various valves, gauges, and sampling ports; GAC vapor treatment; and monitoring wells along with probes (see Figure 1). Two separate pilot systems were installed at Site D. The first pilot system covered an area of 2,500 square feet and was designed to evaluate the effectiveness of vapor extraction for TCE removal from soil that had contamination levels of less than 5 mg/kg. The second system was installed over a 10,000 square feet area that had TCE concentrations greater than 100 mg/kg. Besides the differences in size and initial TCE contamination levels, pilot system no. 1 had an extraction rate of between 40 and 55 cfm. The vent pipe spacing for System 1 was 20 feet, while System 2 had a vent pipe spacing of 50 feet and an extraction rate of between 200 and 220 cfm.

Monitoring was continuous for both systems, with air flow rate, moisture content, temperature, pressure, and hourly TCE concentrations being the primary pieces of data collected. Two full-scale field systems were installed at Sites D and G. The designs were basically the same except that there are no injection wells and that there was no vapor treatment at Site D.

Status of Experiment/Site Clean-up: The following is a summary of the pilot study and the status of the field system.

1. System Number 1 was in operation for 67 days. During that time, 1,874 grams (1.9 lb) of TCE was extracted from the 8,000 cubic feet of contaminated soil. The total daily TCE extraction rate was originally greater than 70 mg/day, but decreased to less than 10 mg/day during the last week of the pilot study.

2. System Number 2 was in operation for 78 days. During that time, 730 kilograms (1,609 lbs.) of TCE were extracted from the 50,000 cubic feet of contaminated soil. On the average, 11 kg/day was removed by this pilot system.

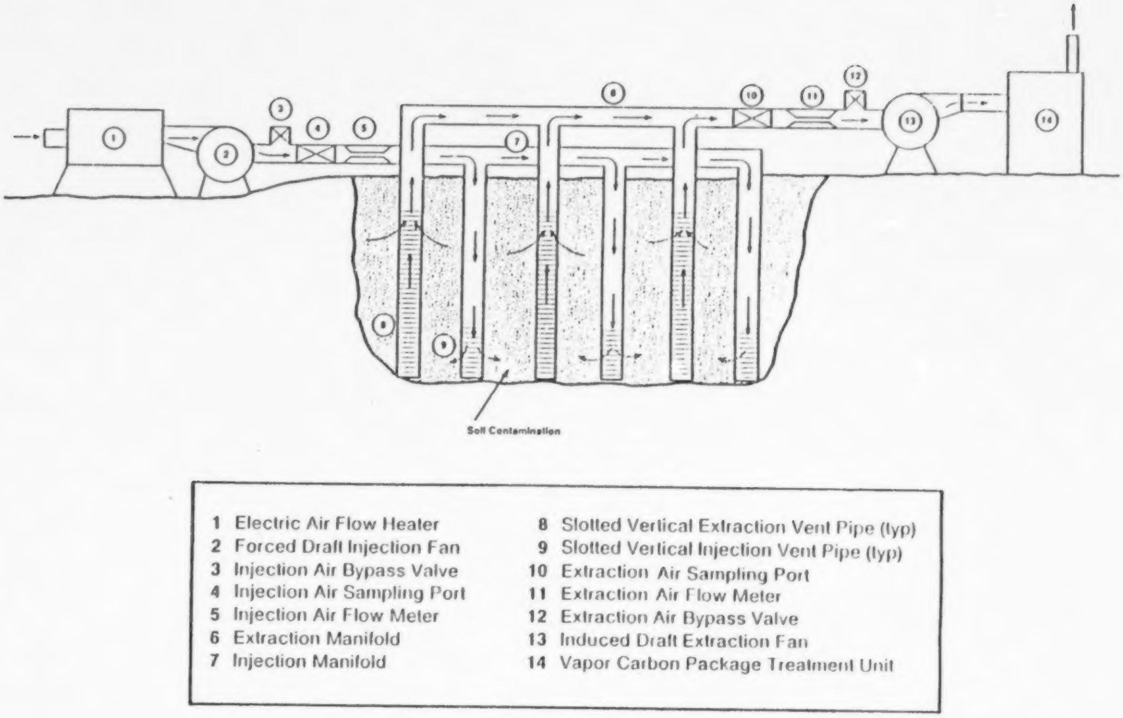
3. Termination of air injection did not effect the extraction rate or the extracted TCE concentrations. Reduction of the extraction flow rates, affected system number 2 by a reduction in the extracted TCE concentrations.

4. Less than 1% of the initial soil moisture was removed during venting for both pilot systems. The temperature range of the extacted air was from 40^0 to 48^0.

5. Vapor extraction costs were estimated to be approximately $15 to $20 per cubic yard, including the costs for soil vapor extraction system hardware, extraction air carbon adsorption system, and soil sampling.

6. Higher recovery rates were observed when the vents were more closely spaced.

The full-scale operation started during the winter of 1986 and is nearing final clean-up.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Soil Contamination
1 Electric Air Flow Heater
2 Forced Draft Injection Fan
3 Injection Air Bypass Valve
4 Injection Air Sampling Port
5 Injection Air Flow Meter
6 Extraction Manifold
7 Injection Manifold
8 Slotted Vertical Extraction Vent Pipe (typ)
9 Slotted Vertical Injection Vent Pipe (typ)
10 Extraction Air Sampling Port
11 Extraction Air Flow Meter
12 Extraction Air Bypass Valve
13 Induced Draft Extraction Fan
14 Vapor Carbon Package Treatment Unit

Figure 1. Soil Vapor Extraction System Design at TCAAP (Source: Anastos et al., 1985).

ASSESSMENT OF LAB-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Texas Research Institute Lab Study

Principal Investigator:
W. L. Wootan, Jr.
Texas Research Institute (TRI), Inc.
Austin, TX

Investigative Reports:

Thornton, S.J., R.E. Montgomery, T. Voynick, and W.L. Wootan, "Removal of Gasoline Vapor from Aquifers by Forced Venting," in Proceedings of the 1984 Hazardous Materials Spills Conference, Nashville, TN, pp 279-286, April 1984.

Wootan, W.L., and T. Voynick, "Forced Venting to Remove Gasoline Vapor from a Large-Scale Model Aquifer," Texas Research Institute, Inc., Final Report to American Petroleum Institute, 1984.

Location of Work/Study:
Texas Research Institute, Inc.
9063 Bee Caves Road
Austin, TX 78746

Nature of Contamination: The feasibility of vapor extraction systems was studied in model aquifers designed and constructed by the Texas Research Institute. A total of 80 liters of unleaded gasoline was intentionally spilled in two separate tanks at four points (see Figure 1). Gasoline was added to the sand just above the capillary zone and was allowed to spread through the model aquifer before vapor extraction was started.

Site/Soil Conditions: Each model aquifer consisted of a 3 meters by 3 meters by 1.2 meters deep concrete tank packed with washed river sand. Each tank was insulated, and the interior temperature was maintained at 13°C. Each of the tanks had flowing water with a water table set at 8 to 30 cm deep as shown in Figure 2.

Experimental/System Design: The lab-scale soil vapor extraction system consisted of air inlet vents and a central extraction well; a concrete cap; a blower; flow meters; various plumbing, valves, and sampling ports; a gasoline/water separator; and various thermocouples, vapor, and observation wells. A steel partition separated the two tanks. The partition was sealed with silicone caulk, and the seams and joints were covered with fiberglass and polyester resin. Water entered the sand pack near the steel partition through a perforated PVC pipe, 2.5 meters long. This PVC pipe was suspended 20 cm from the bottom of the tank. A 15 cm high standpipe/extraction well at the center of the opposite wall allowed water and gasoline to flow out of the tank and into the separator. In the separator, the raw gasoline was collected for measurement. The effluent water was pumped to a holding tank from which it was periodically transported to a sewage treatment facility.

The eight observation wells were made from 3.2 cm PVC pipe slotted from the floor of the tank to 60 cm. Four of these observation wells were also used as gasoline spill sites as shown on Figure 1. The vapor wells were placed at depths of 20 and 65 cm. A Sutton, Model PB-55A blower was used to create a pressure drop of about 0.44 inches of mercury at each extraction pipe.

Four experiments were run. The first two experiments (A & B) compared the air flow paths of two test cells. Cell A had a flow path from the inlet well 56 cm tall, extending from the top of the capillary zone to just below the top of the tank. The flow path in cell B was modified by screening only 15 cm of the air inlet well just above the capillary zone. See Figure 3 for the air flow patterns for experiments A & B, Phase I. Air flow rates of 4 and 16 liters per minute were used for both experiments (4 L/min for one week for both test cells and then 16 L/min for one week, again for both test cells). The third and fourth experiments used thicker flow paths (75 and 58 cm., respectively, for Experiments C and D) to vent sand packs of two different permeabilities (medium-grained Finish sand with a hydraulic conductivity of 4.2 x 10^{-2} cm/sec. and fine-grained mortar sand with a hydraulic conductivity of 3.1 x 10^{-2} cm/sec) at air flow rates of 0.4, 1.0, and 4.0 L/min. Figures 4, 5, and 6 show the tank set-up and airflow patterns for Phase II of the experiments. Each tank had instruments that could monitor temperature, water levels, water flow rates, air flow rates, and gasoline vapor concentration in the sand. Three types of gasoline removal were studied: 1. Raw gasoline flowing out of the tank on top of the effluent water, 2. Dissolved gasoline flowing out in the effluent water, and 3. Gasoline vapor swept out of the sand pack with the effluent air. Residual gasoline levels still in the sand, were estimated by analysis of core samples of the sand pack.

Status of Experiment/Site Clean-up: All venting geometries and flow rates were effective in removing gasoline from the sand packs. Both geometries and flow rates were also effective in reducing the gasoline vapor concentrations in the upper half of the tank to less than 1000 ppmv hydrocarbons. This represents a total gasoline vapor recovery of 21.6 liters (27% of the original gasoline present) over the 22 days that the experiment was performed. Screening geometry only had an effect at low air flow rates where it was shown that screen placement near the water table resulted in higher recovery rates than when the well was screened the full depth of the unsaturated zone. Coarse-grained materials were more amenable to vapor extraction because the VOCs were able to diffuse out of the immobile zones at a faster rate. The rate of removal was higher for the higher air flows.

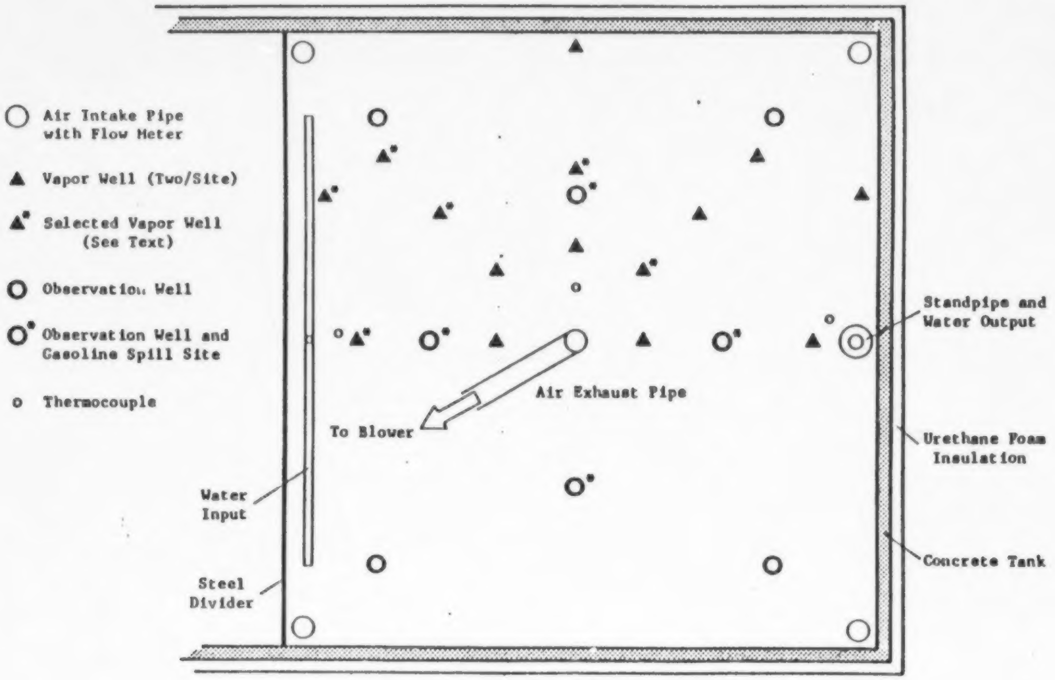

Air Intake Pipe with Flow Meter
Vapor Well (Two/Site)
Selected Vapor Well (See Text)
Observation Well
Observation Well and Gasoline Spill Site
Thermocouple
Standpipe and Water Output
Air Exhaust Pipe
To Blower
Urethane Foam Insulation
Water Input
Concrete Tank
Steel Divider

Figure 1. Plan View of Experimental Tank Set-up for Phase I Study (Source: Wootan and Voynick, 1984).

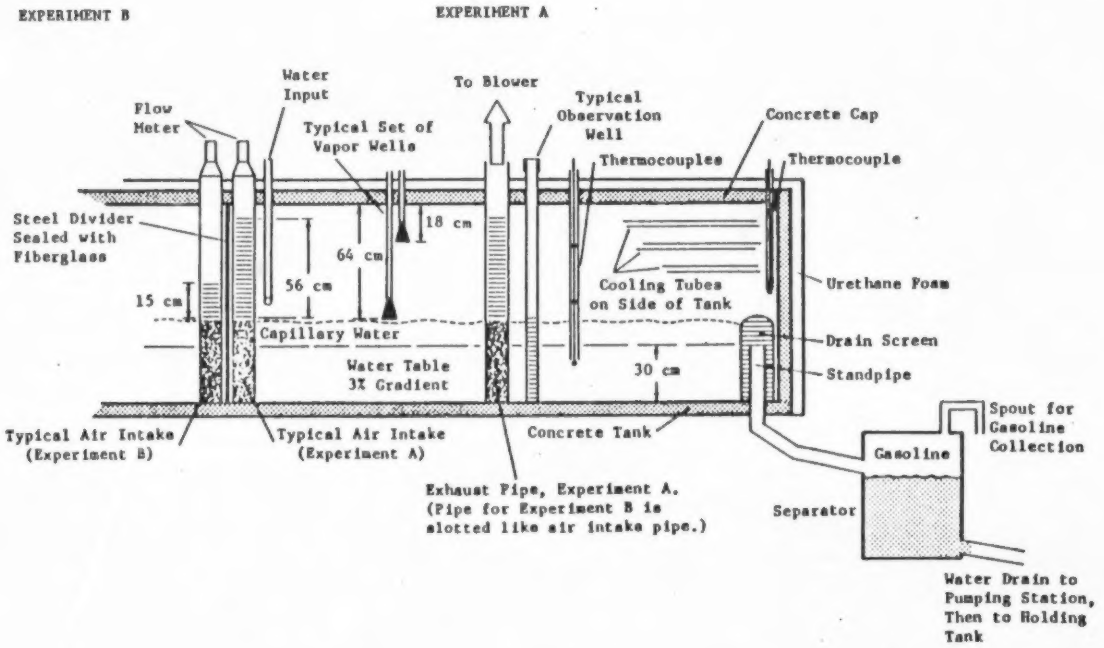

EXPERIMENT B
EXPERIMENT A
Flow Meter
Water Input
Typical Set of Vapor Wells
To Blower
Typical Observation Well
Concrete Cap
Thermocouples
Thermocouple
Steel Divider Sealed with Fiberglass
18 cm
64 cm
56 cm
15 cm
Cooling Tubes on Side of Tank
Urethane Foam
Capillary Water
Drain Screen
Water Table 3% Gradient
30 cm
Standpipe
Typical Air Intake (Experiment B)
Typical Air Intake (Experiment A)
Concrete Tank
Spout for Gasoline Collection
Gasoline
Exhaust Pipe, Experiment A. (Pipe for Experiment B is slotted like air intake pipe.)
Separator
Water Drain to Pumping Station, Then to Holding Tank

Figure 2. Cross-section of Experimental Tank for Phase I Study (Source: Wootan and Voynick, 1984).

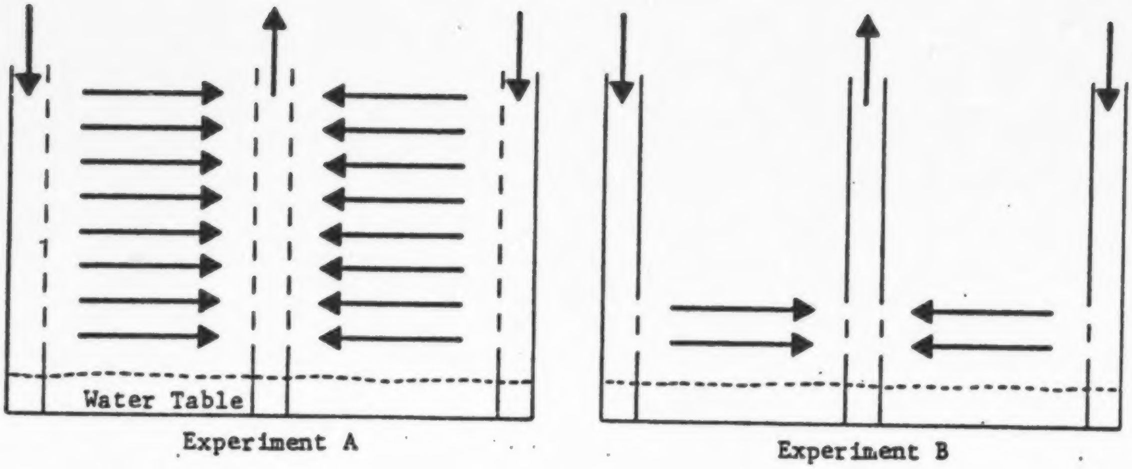

Water Table
Experiment A
Experiment B

Figure 3. Air Flow Patterns for Phase I Study (Source: Wootan and Voynick, 1984).

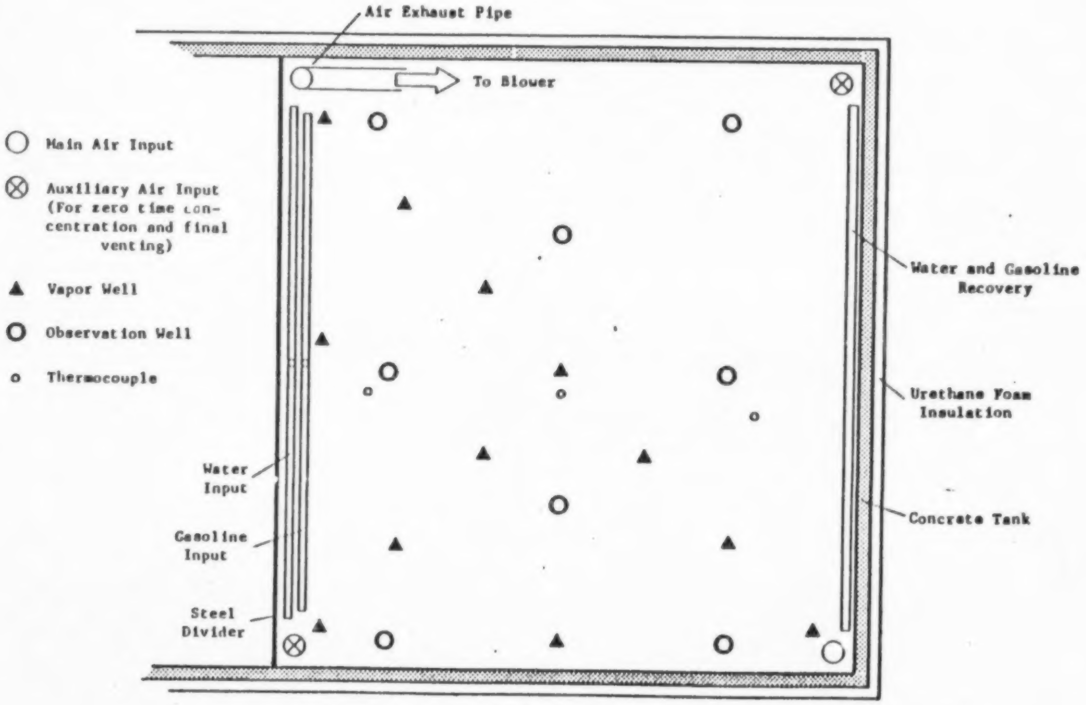

Air Exhaust Pipe
To Blower
○ Main Air Input
⊗ Auxiliary Air Input (For zero time concentration and final venting)
▲ Vapor Well
○ Observation Well
o Thermocouple
Water and Gasoline Recovery
Urethane Foam Insulation
Concrete Tank
Water Input
Gasoline Input
Steel Divider

Figure 4. Plan View of Experimental Tank Set-up for Phase II Study (Source: Wootan and Voynick, 1984).

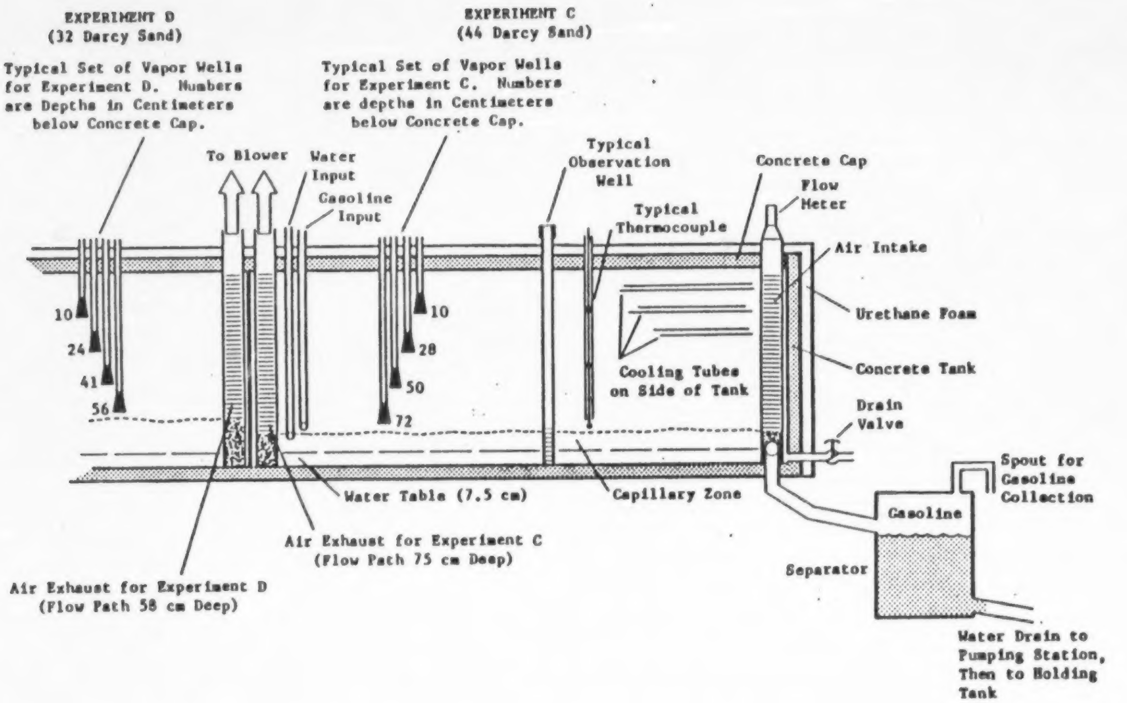
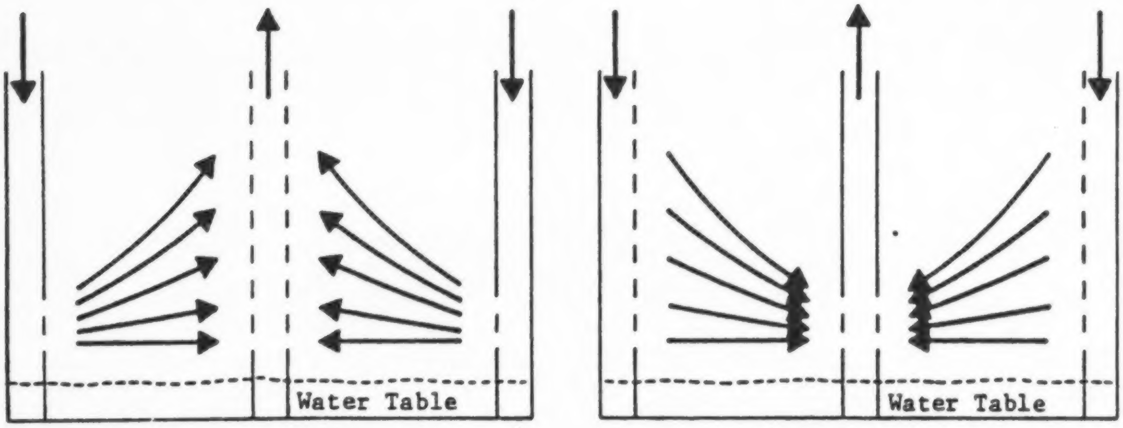

EXPERIMENT D
(32 Darcy Sand)
Typical Set of Vapor Wells for Experiment D. Numbers are Depths in Centimeters below Concrete Cap.
EXPERIMENT C
(44 Darcy Sand)
Typical Set of Vapor Wells for Experiment C. Numbers are depths in Centimeters below Concrete Cap.
To Blower
Water Input
Gasoline Input
Typical Observation Well
Typical Thermocouple
Concrete Cap
Flow Meter
Air Intake
Urethane Foam
Concrete Tank
Cooling Tubes on Side of Tank
Drain Valve
Spout for Gasoline Collection
Gasoline
Separator
Water Drain to Pumping Station, Then to Holding Tank
10
24
41
56
10
28
50
72
Water Table (7.5 cm)
Capillary Zone
Air Exhaust for Experiment C (Flow Path 75 cm Deep)
Air Exhaust for Experiment D (Flow Path 58 cm Deep)

Figure 5. Cross-section of Experimental Tank for Phase II Study (Source: Wootan and Voynick, 1984).


Water Table
Water Table

Proposed for Phase II **Proposed for Phase II**

(Arrows Represent Air Flow Patterns)

Figure 6. Air Flow Patterns for Phase II Study (Source: Wootan and Voynick, 1984).

ASSESSMENT OF LAB-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Tysons Lagoon Superfund Site

Principal Investigator:
AWARE Incorporated
621 Mainstream Drive
Suite 200, Metro Center
Nashville, TN

Site Investigation Report:

AWARE, Inc., "Phase I - Zone I Soil Decontamination Through In-Situ Vapor Stripping Processes," (Contract Number 68-02-4446), Final Report, Prepared for: U.S. Environmental Protection Agency, Small Business Innovative Research Program , Washington, D.C. Prepared by: AWARE, Inc., 621 Mainstream Drive, Suite 200, Metro Center, Nashville, TN 37228, April 1987.

Location of Work/Study: CIBA-GEIGY Corporation spill site at Tysons Lagoon, Pennsylvania

Nature of Contamination: Soil Column 1 -- Significant quantities of TCE, trichloropropane (TCP), toluene, ethyl benzene, and xylene plus another compound at extremely high concentrations tentatively identified as 1,1,1,2-tetrachloroethane. Soil Column 2 -- Soil concentrations significantly lower than those from Column 1 with toluene, ethyl benzene and xylene being the major components stripped.

Soil/Site Conditions:
Soil type = sandy
Moisture content = 16%
Organic content = 4.4%
% Porosity = 54%

The soil samples tended to clump together and were difficult to pack even though sandy and at moderately low moisture content.

Experimental/System Design: Same setup as the AWARE study (see AWARE.SHT) with the exceptions that the soil in column 1 was 15 mm deep and the soil in column 2 was 300 mm deep. The initial air flow rate was 2 mL/min. Two air samples (20 mL and 5 mL) were collected from each column immediately after stripping began. Initial volatile organic emissions were extremely high and resulted in a multitude of peaks on the gas chromatograph which could not be easily identified or quantified. After 24 hours of stripping, a multitude of peaks again occurred on the gas chromatograph, so the air flow rates were increased to 3.5 mL/min to speed up the soil stripping process. The stripping process was continued at this rate for the experiment's duration of 11 days.

Status of Experiment/Site Clean-up: Significant quantities of TCE, trichloropropane (TCP), toluene, ethyl benzene, and xylene were stripped from Column 1 during the 11 days of this study as summarized in Table 1. The gas concentrations extracted from Column 2 were significantly lower than those from column 1. This was expected, since the initial concentrations in column 2 were considerably lower at the beginning of this study. Toluene, ethyl benzene, and xylene were the major compounds stripped from column 2. Table 1 also records the percent removals for each of the columns.

A full-scale soil vapor extraction system has reportedly been installed at the Tyson site (Peter Michaels, personal communication, June 1988).

Table 1: Methanol Extraction of Soil Samples

Soil Analysis For Column 1

Compound	Initial Concentration (ug/g)	Final Concentration (ug/g)	Percent Removals
Toluene	600	10	98
Ethyl Benzene	1,100	60	95
p, m-Xylene	11,700	334	97
o-xylene	3,700	192	95
1,2,3-TCP	2,600	10	99

Soil Analysis For Column 2

Compound	Initial Concentration (ug/g)	Final Concentration (ug/g)	Percent Removals
Toluene	37	10	73
Ethyl Benzene	74	41	45
p, m-Xylene	970	255	74
o-Xylene	280	100	64
1,2,3-TCP	100	10	90

(Source: AWARE, 1987)

ASSESSMENT OF FULL-SCALE VAPOR EXTRACTION SYSTEMS

SITE DATA SHEET

Site/Project Name: Verona Well Field/Thomas Solvents Raymond Road Facility -- Superfund Site

Principal Investigators:
John Tanaka, Project Manager
USEPA, Region V
230 S. Dearborn St.
Chicago, IL 60604

CH_2M-Hill
Reston, VA

Investigative Reports:

CH_2M-Hill, Inc., Remedial Planning/Field Investigation Team, "Verona Well Field - Thomas Solvent Company, Battle Creek, Michigan, Operable Unit Feasibility Study," Contract No. 68-01-6692, June 17, 1985.

CH_2M-Hill, Inc., "Operable Unit Remedial Action, Soil Vapor Extraction at Thomas Solvents Raymond Road Facility, Battle Creek, MI, Quality Assurance Project Plan," October, 1987a.

CH_2M-Hill, Inc., "Appendix B - Sampling Plan, Operable Unit Remedial Action; Soil Vapor Extraction At Thomas Solvents Raymond Road Facility, Battle Creek, MI," October, 1987b.

Location of Work/Study: Thomas Solvents Company Raymond Road Facility, Battle Creek, MI. See Figure 1 for location of site.

Nature of Contamination: The major public potable water source in Battle Creek, Michigan, is the Verona Well Field, which serves 35,000 residents and a number of commercial and industrial establishments. In August 1981, the Calhoun County Health Department discovered and later verified that nearly one-half of Battle Creek's 30 potable wells were contaminated with VOCs. By January 1984, all but six of the city's wells were affected by the groundwater contamination plume.

Two of the major contaminant sources were the Thomas Solvents sites (Raymond Road and the Emmett Street Annex). Thomas Solvents Company stored, transferred, and packaged chlorinated and nonchlorinated solvents. In addition, Thomas Solvents Company handled liquid industrial wastes. In all, there were 21 underground storage tanks on the site. The contamination resulted from tank leakage and from spillage from above-ground transfer of chemicals. Another source of contamination was the Grand Trunk Western Railroad's marshaling yard where DOWCLENE (a commercial solvent formulated from PCE and 1,1,1-TCA) was disposed of during rail-car operations.

The major constituents of both plumes were PCE (tetrachloroethylene or perchloroethylene) and 1,1,1-Trichloroethane (1,1,1-TCA). In addition, the combined Thomas Solvents' plume contains TCE. Table 1 lists all chemical contaminants encountered at these sites. It is possible that some of the chemicals were the the result of the degradation of PCE, TCE and 1,1,1-TCA. Sixty-eight percent (3,900 pounds of VOCs at levels exceeding 100,000 ppb) of the total contaminant mass in the southern plume is located beneath the Raymond Road Facility. The total VOC mass in the unsaturated zone on the Raymond Road Facility is estimated to be approximately 1,700 pounds. It is estimated that there are 440 pounds of VOCs in the saturated zone directly underneath the property

Soil/Site Conditions: In general, the aquifer consists of two units: a sand and gravel alluvial deposit overlying the sandstone of the Marshall Formation (bedrock). The municipal well field is within this bedrock layer. The sand and gravel layer varies in thickness from 13.5 feet to a maximum of 45 feet and consists of fine to medium sand with 3 to 6% silt and clay size grains. The average hydraulic conductivity of the sand is approximately 0.1 cm/sec (274 feet/day). However, a conservative estimate of 0.04 cm/sec (120 feet/day) was used for determining groundwater clean-up rates. The current groundwater flow through the sand and gravel layer is to the northwest across the property and is estimated to be 1 to 2 feet/day. The Marshall Formation (bedrock) layer consists of fine to medium grained, well-cemented sandstone with the upper 5 to 20 feet weathered. The hydraulic conductivity of the upper bedrock is approximately 0.06 cm/sec (170 feet/day). The aquifer's vertical hydraulic conductivity is lower than the horizontal hydraulic conductivity. Based on modeling by CH_2M-Hill, the resistance to vertical flow was thought of as a low conductivity layer between the sand and gravel layer; and the sandstone bedrock layer with a hydraulic resistance of 0.01/day. There is a shale formation at about a depth of 140 feet to provide the only natural means of confinement.

Experimental/System Design: The soil vapor extraction system consists of extraction wells; a vacuum pump; a gas flow meter; various plumbing, valves, gauges, and sampling ports; GAC vapor treatment; and monitoring wells. The vapor extraction system is being used to remove VOCs from the unsaturated zone at Thomas Solvents Raymond Road site, while groundwater pumping with subsequent GAC water treatment is being utilized to treat the contaminated groundwater. The system consists of fourteen 4-inch PVC wells with perfo well screens extending into the groundwater, packed with gravel, and sealed at the top with bentonite to prevent short circuiting of air flows. The extraction wells are connected to the suction side of a 25-hp, 960 cfm vacuum extraction unit via a surface collection manifold. The operation of the vapor extraction system induces clean air flow from the atmosphere into the subsoils. This system is designed to decrease the pressure in the soil voids, resulting in additional VOCs being released. The extracted soil gas flows through the manifold system to vapor phase activated carbon adsorption canisters. The extracted gas is then discharged through a 30-foot stack into the atmosphere. A backup carbon system is on-line continuously to prevent carbon breakthrough. An alarm for VOCs entering the backup carbon system, indicating primary carbon absorption unit breakthrough is provided.

Status of Experiment/Site Clean-up: This site is currently undergoing active treatment utilizing Terra Vac system.

Table 1. Chemicals Present in Verona Well Field Site Soils (Source: CH_2M-Hill, 1985)

Chlorinated Hydrocarbons

- methylene chloride
- chloroform
- carbon tetrachloride
- 1,2-dichloroethane (DCA)
- 1,1,1-trichloroethane (TCA)
- vinyl chloride
- 1,1-dichloroethylene (DCE)
- trans-1,2-dichloroethylene
- trichloroethylene (TCE)
- tetrachloroethylene (PCE)

Aromatic Hydrocarbons

- benzene
- toluene
- xylene
- ethyl benzene
- naphthalene

Ketones

- acetone
- methyl ethyl ketone
- methyl isobutyl ketone